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Cordani

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(54) **METHOD OF MODIFYING WEATHER**

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(22) Filed: **Jun. 21, 2000**

(51) **Int. Cl.**[7] **A01G 15/00**
(52) **U.S. Cl.** **239/2.1**; 239/14.1; 252/194
(58) **Field of Search** 239/2.1, 14.1; 252/194

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4,600,147		7/1986	Fukuta et al.	239/14.1
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Primary Examiner—Joseph D. Anthony
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(57) **ABSTRACT**

A method for artificially modifying the weather by seeding rain clouds of a storm with suitable cross-linked aqueous polymer. The polymer is dispersed into the cloud and the wind of the storm agitates the mixture causing the polymer to absorb the rain. This reaction forms a gelatinous substance which precipitate to the surface below. Thus, diminishing the clouds ability to rain.

7 Claims, No Drawings

METHOD OF MODIFYING WEATHER

FIELD OF THE INVENTION

This invention relates generally to weather modification and in particular to the use of polymers to absorb aqueous solutions capable of modifying a weather situation.

BACKGROUND OF THE INVENTION

Hurricanes, tropical storms, typhoons, and the like weather patterns can cause severe damage to land, buildings, and living creatures. The resulting damage from even an isolated event can be billions of dollars as evidenced by Hurricane Andrew.

Cloud seeding is a known process for artificially modifying the weather by injecting a composition into a cloud for formation of an ice freezing nuclei. Silver iodide is a well known substance used for cloud seeding. Ice freezing nuclei have the effect of creating rain, reducing hail, and possibly preventing rain by overseeding.

U.S. Pat. No. 5,174,498 discloses a cloud seeding material useful for seeding supercooled clouds in order to augment rainfall. The material used in seeding is defined as a aliphatic long-chain alcohol.

U.S. Pat. No. 4,600,147 discloses a cloud seeding method of inserting liquid propane from a rocket. The liquid propane is used to generate large numbers of ice crystals in supercooled clouds.

U.S. Pat. No. 5,357,865 discloses yet another method of cloud seeding. This invention includes the use of a pyrotechnic composition such as potassium chlorate or potassium perchlorate which act as nuclei for precipitable water drop formation.

U.S. Pat. No. 4,096,005 discloses a pyrotechnic cloud seeding composition comprising silver iodate and a fuel from the consisting of aluminum and magnesium.

Thus, the prior art teachings are directed to methods of creating rain. What is lacking in the art is a method of lessening the wind velocities of a storm.

SUMMARY OF THE INVENTION

The instant application discloses a method of modifying weather by seeding storm clouds with a polymer. The storm clouds are seeded by dispersing a superabsorbent polymer into the cloud in sufficient quantities to cause a large absorption of water. The reaction of the water with the polymer creates a gel-like substance that precipitates to the surface. Thus, causing an internal constriction with the cloud to lessen storm velocities.

A superabsorbent polymer is a resin capable of absorbing water up to several thousands times as its own weight. These superabsorbent polymers are prepared from water-soluble polymers, but have cross-linking structures which render the polymers water-insoluble. By taking water-soluble ethylenically unsaturated monomers which readily undergo vinyl polymerizaton, such as acrylamide, with the use of cross linking agents, a polymer can be produced that is of uniform small size, has a high gel capacity, is highly insoluble, but highly water swellable i.e. a superabsorbent polymer. (Gel capacity refers to the property of the water swollen polymer to resist viscosity changes as a result of mechanical working or milling.)

Superabsorbent polymers can be dehydrated to a powder. When the powder is added to an aqueous solution and agitated, the polymer is able to absorb many times its weight of the water molecules and a gel-like substance is formed. Superabsorbent polymers are particularly suited for uses where rapid sorption of aqueous fluid is desired or for uses where the swelling properties in water are employed.

Accordingly, it is an objective of the instant invention to present a method for artificially modifying weather wherein a polymer is used to cause wind dissipation by heaving weighting condensation with the clouds.

It is another objective of the instant invention to present a method for seeding a rain cloud with a cross-linked polymer such that the wind of the storm provides the agitation for the reaction of the polymer with the water.

It is an additional objective of the instant invention to present a method for modifying storms such that the solid end product is biodegradable and nonhazardous.

Other objectives and advantages of this invention will become apparent from the following description wherein are set forth, by way of example, certain embodiments of this invention.

DETAILED DESCRIPTION OF THE INVENTION

It is to be understood that while a certain form of the invention is illustrated, it is not to be limited to the specific form or arrangement of parts herein described and shown. It will be apparent to those skilled in the art that various changes may be made without departing from the scope of the invention and the invention is not to be considered limited to what is shown and described in the specification and drawings.

The present invention relates to a method for artificially modifying weather by solidifying portions of a cloud in a storm such as a hurricane, by introducing polymers into the cloud. This method utilizes "superabsorbent" aqueous based polymers, preferably cross linked modified polyacrylamides which can be used in any application where aqueous solidification is permissible. An example of a superabsorbent aqueous based polymer is manufactured by JRM Chemical Inc. under the trademark H-series.

In the present invention, a solid form of the superabsorbent polymer, such as a powder, is introduced into the rain clouds of a storm in a suitable manner, for instance a aircraft may traverse the storm and release the polymer seeds or they may be released from a seeding flare delivered from the surface or from an aircraft. The amount of polymer needed is predetermined based upon the size and severity of the storm along with the absorption capacity of the polymer used. The wind of the storm provides the agitation that causes the polymer to bind with the water forming a gel-like substance. As a result of this method, wind based water storms can be artificially modified.

The use of a biodegradable polymer allows for safe use of the ocean wherein the high salinity of the water will expedite the degradation of the material. Various biodegradable superabsorbent polymers include carboxy-methylcellulose, alginic acid, cross-linked starches, cross-linked polyamino acids and a cross-linked modified polyacrylamides.

In a dry state the preferred polymer may be considered a particle having a diameter less than 4000 microns but greater than 50 microns. In a swollen state the particle may have a diameter greater than three hundred times its weight. In a totally water-swollen state, the particles contain up to about 99.98 weight percent of water and a little as about 0.1 weight percent of polymer. Thus, such particles could hold from ten to thousands of times their own weight. By seeding a leading

edge of a violent storm, such as a hurricane, the winds cause a mix of the material wherein moisture is absorbed by the material causing a shearing effect. The shearing effect causes the polymers to absorb, lose, and reabsorb water countless times. During this exchange, the weight of the water being transferred allowing for wind shearing that assists in lessening the velocity of the wind.

The shearing forces are affected by the nature of the interactions between the particles during such collisions. When attractive forces dominate, the particles will aggregate and the dispersion may destabilize.

Example: A hurricane is seeded with approximately 30,000 lbs of a superabsorbent aqueous based polymer by use of a transport plane flying through the leading edge of the storm. Within twenty seconds the polymer will obtain over 70 percent of its absorption capacity or nearly three hundred times its weight. The winds of the storm will continue to disperse the materials causing a form of internal flocculation disrupting the feeding nature of the storm. When presented close to land, the storm will not have sufficient time to reform to its previous strength.

It is to be understood that while I have illustrated and described certain forms of my invention, it is not to be limited to the specific forms herein described: It will be apparent to those skilled in the art that various changes may be made without departing from the scope of the invention and the invention is not to be considered limited to what is shown in the drawings and described in the specification.

What is claimed is:

1. A method for artificially modifying weather by seeding a rain cloud comprising:

forming an aqueous solidifier material capable of retaining over three hundred times its own weight in water, wherein said aqueous solidifier material is a cross-linked aqueous based polymer; dispersing said material into a suitable cloud formation, wherein the wind generated by the storm causes said solidifier to mix with rain to form a gel like substance;

said gel like substance being of sufficient weight to precipitate to the surface below thereby diminishing the velocity of the cloud.

2. The method of claim 1 wherein said dispersion of aqueous solidifier is from an aircraft traversing the cloud.

3. The method of claim 1 wherein said dispersion of aqueous solidifier is from the surface below.

4. The cross-linked aqueous polymer of claim 1 wherein said polymer is a cross-linked modified polyacrylamides.

5. The cross-linked polymer of 1 wherein said material is between 50 and 4000 microns.

6. The method of claim 1 wherein the amount of said aqueous solidifier needed is precalculated based upon the size of the storm and the absorption properties of said aqueous solidifier.

7. The methods of claim 1 wherein said aqueous solidifier is biodegradable and nonhazardous.

* * * * *

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(12) **Patent Application Publication**
Bowers et al.
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(43) **Pub. Date: Jul. 9, 2009**

(54) **WATER ALTERATION STRUCTURE APPLICATIONS AND METHODS**

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(21) Appl. No.: **12/006,805**

(22) Filed: **Jan. 3, 2008**

Related U.S. Application Data

(63) Continuation-in-part of application No. 12/006,815, filed on Jan. 3, 2008, Continuation-in-part of application No. 12/006,823, filed on Jan. 3, 2008, Continuation-in-part of application No. 12/006,804, filed on Jan. 3, 2008.

Publication Classification

(51) **Int. Cl.**
F03B 11/00 (2006.01)
F17D 1/00 (2006.01)

(52) **U.S. Cl.** .... 137/1; 137/561 R

(57) **ABSTRACT**

A method is generally described which includes environmental alteration. The method includes determining a placement of at least one vessel capable of moving water to lower depths in the water via wave induced downwelling. The method also includes placing the at least one vessel in the determined placement. Further, the method includes generating movement of the water adjacent the surface of the water in response to the placing.

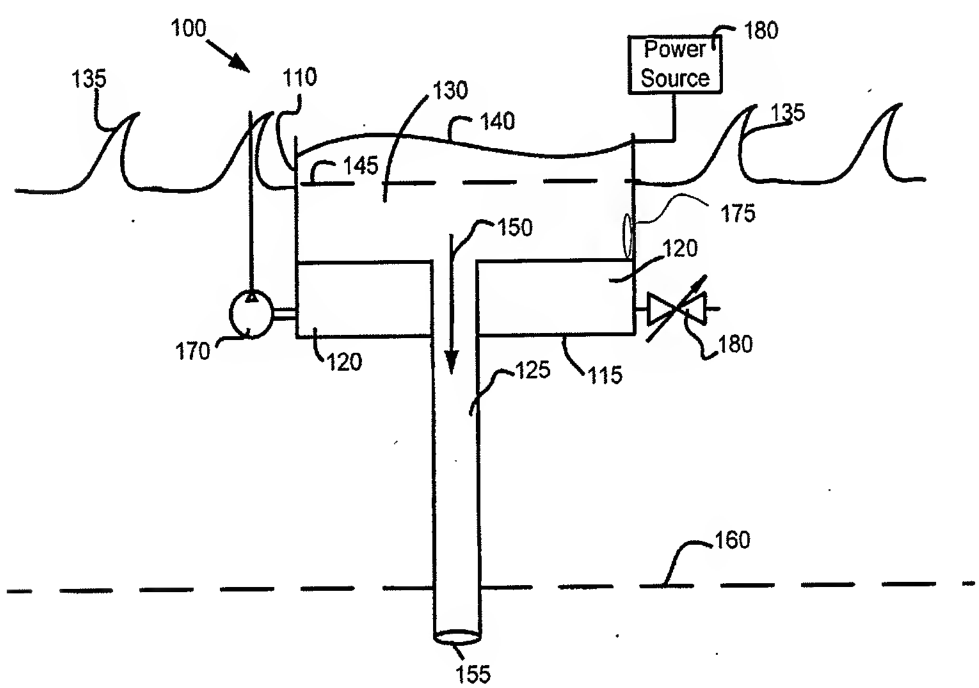
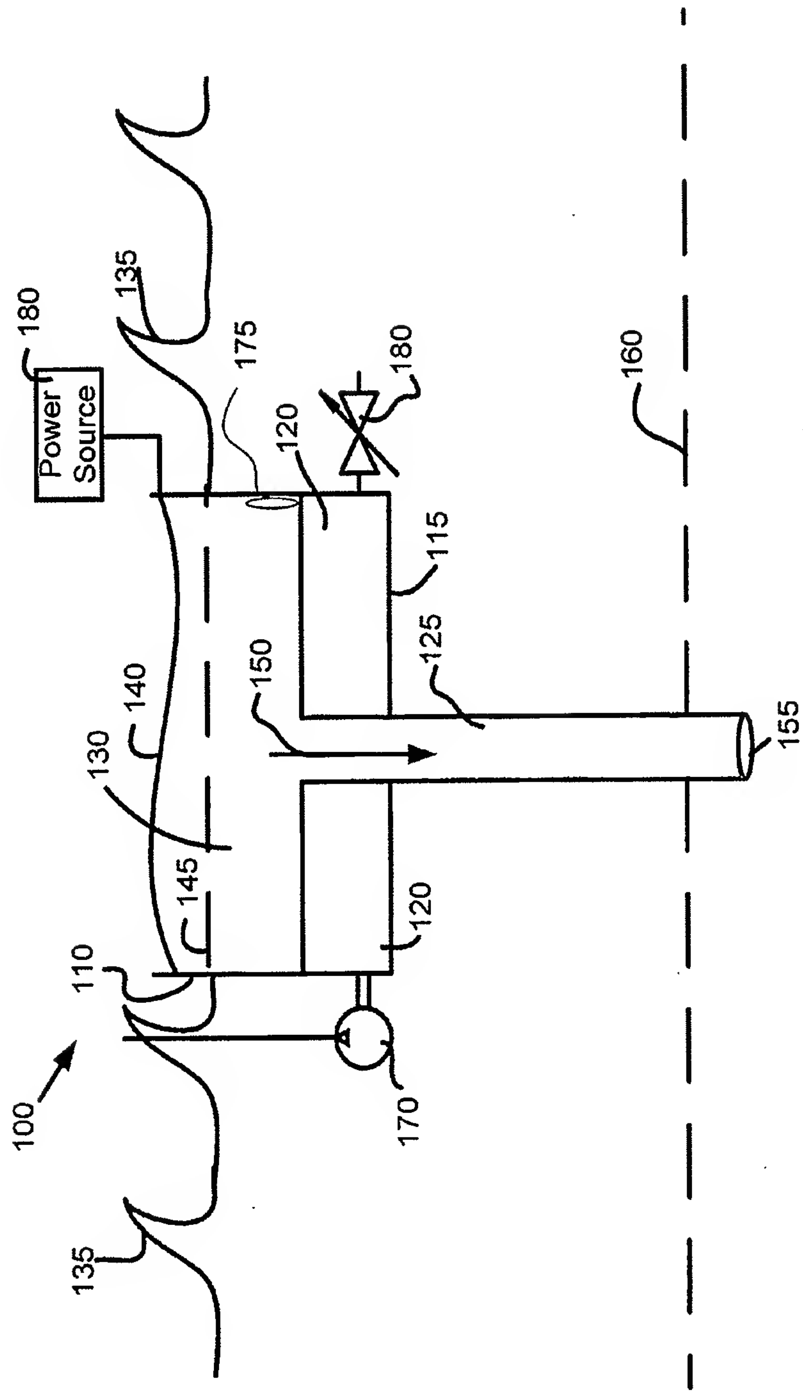


FIG. 1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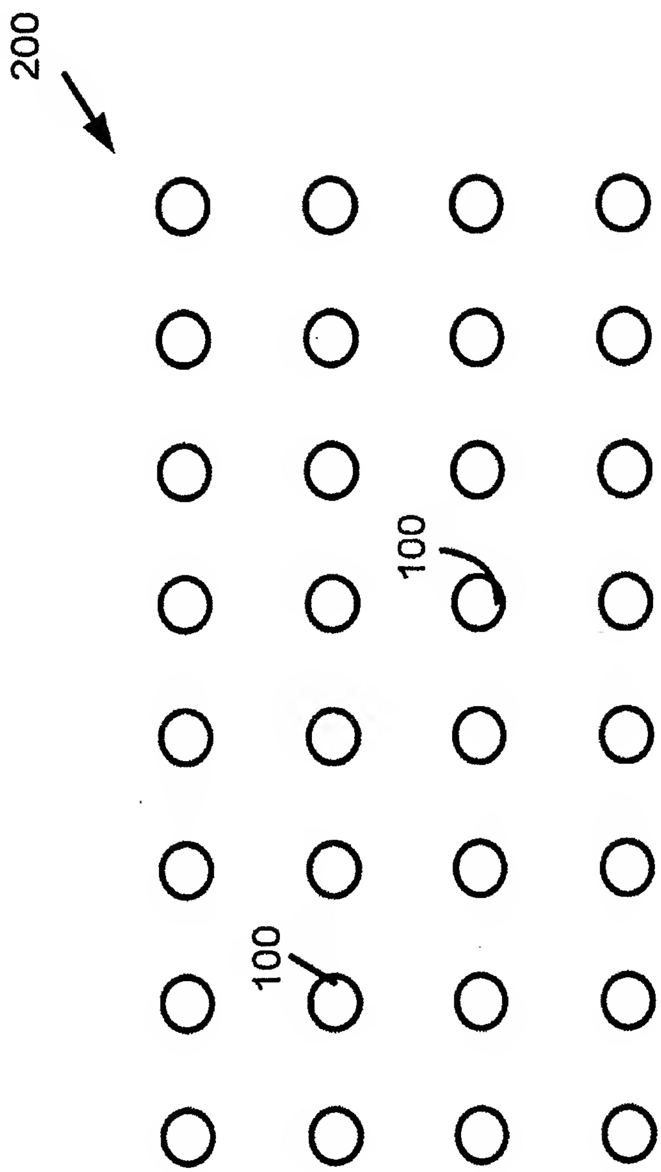


FIG. 2

FIG. 3

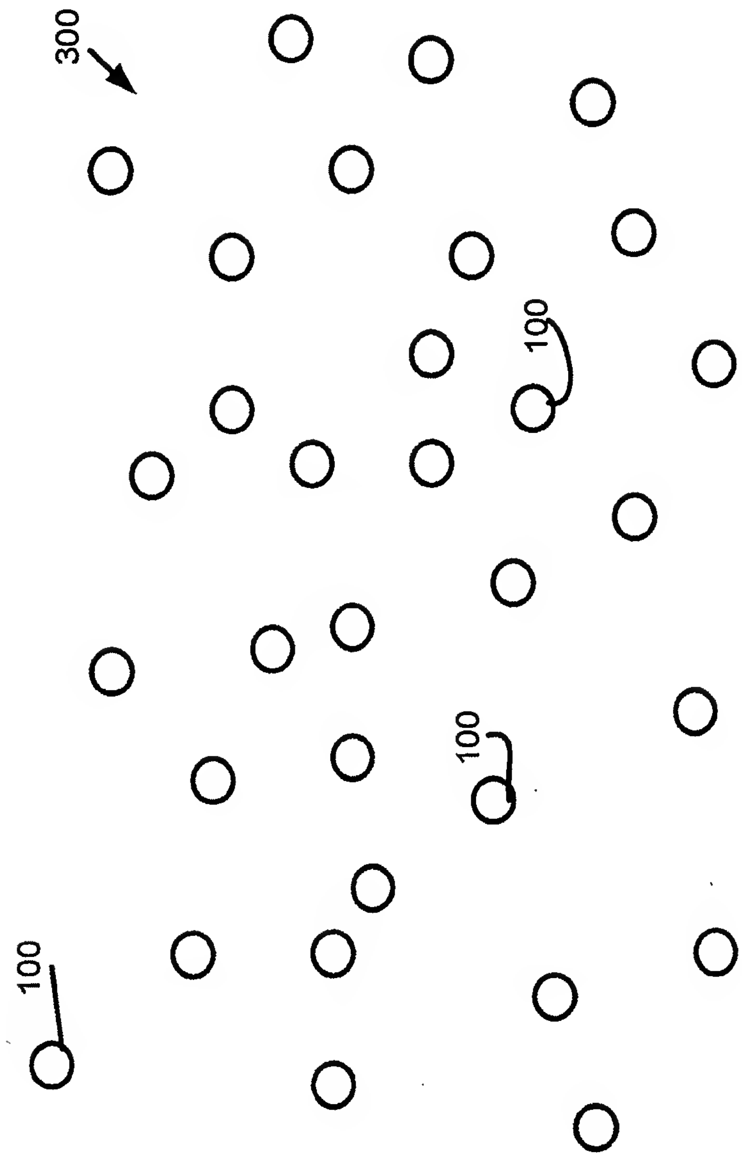
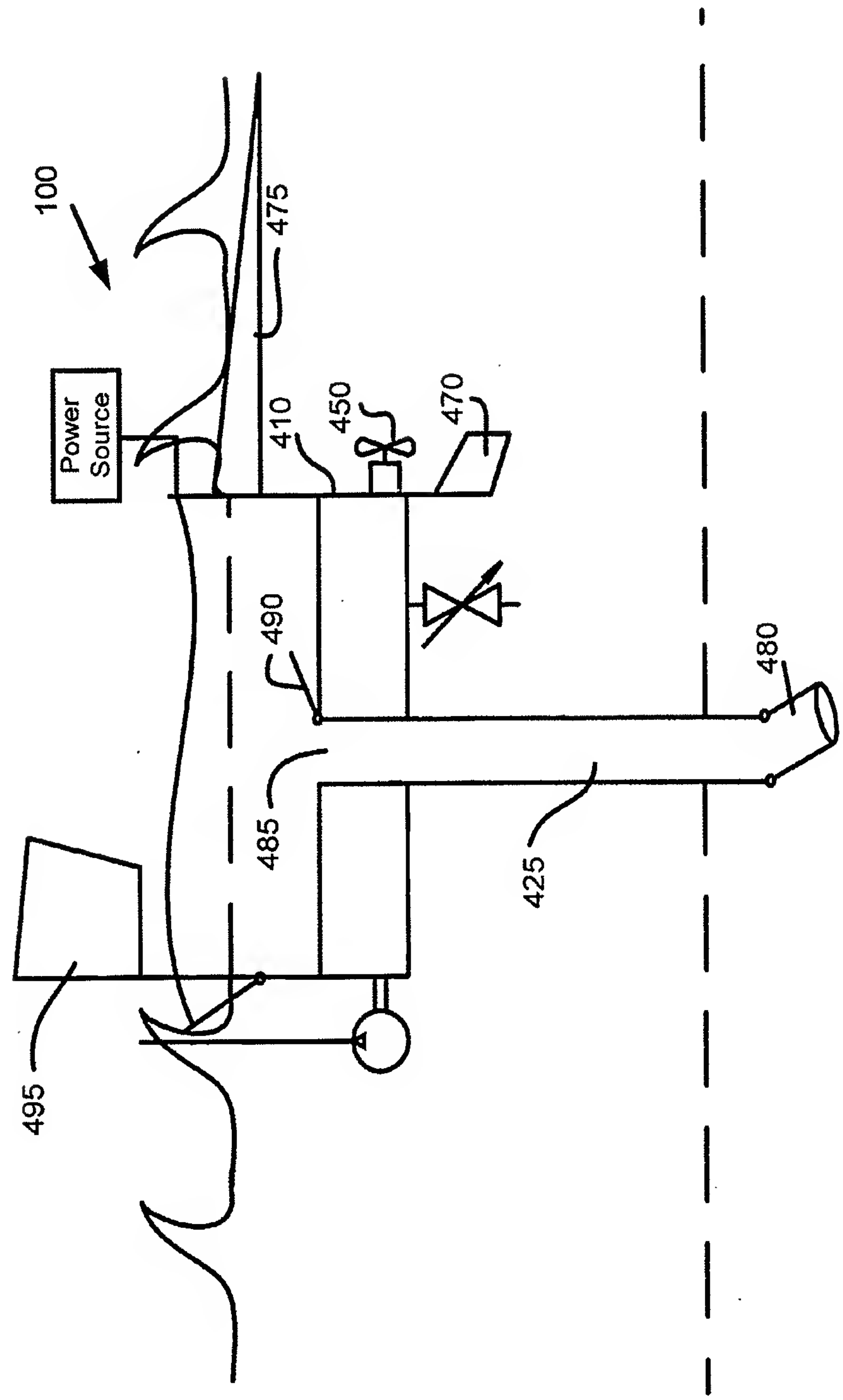


FIG. 4



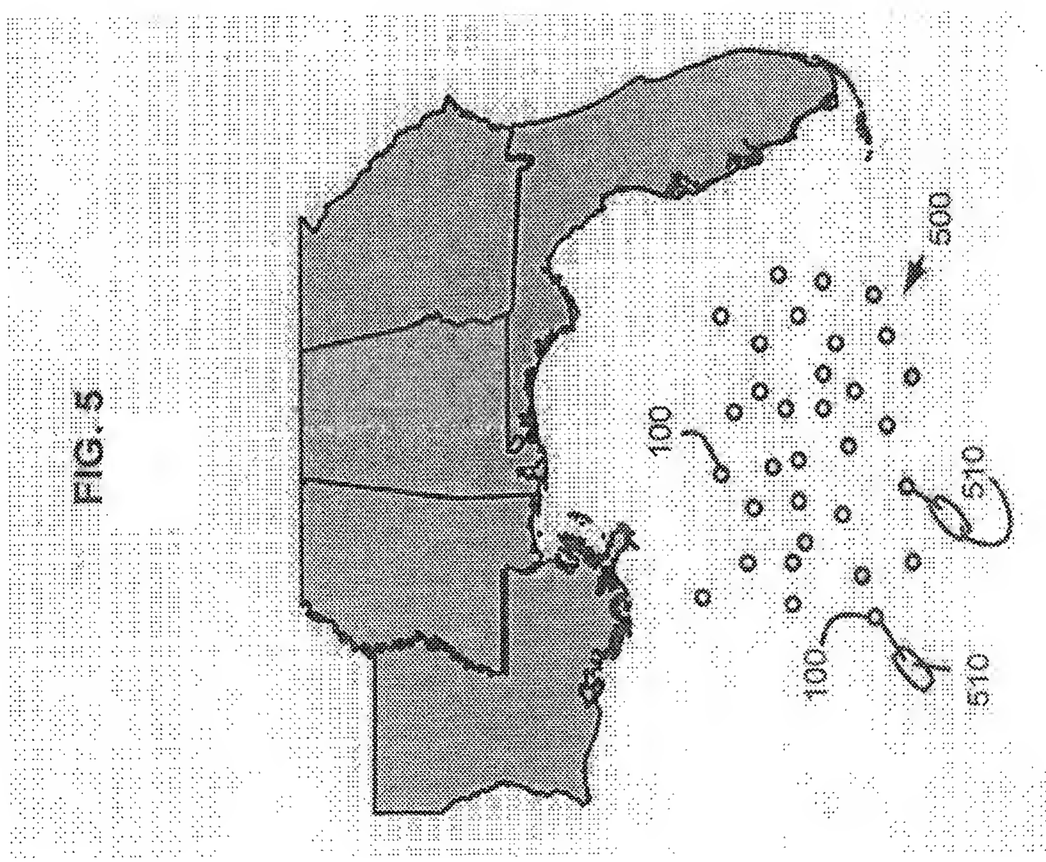


FIG. 5

FIG. 6

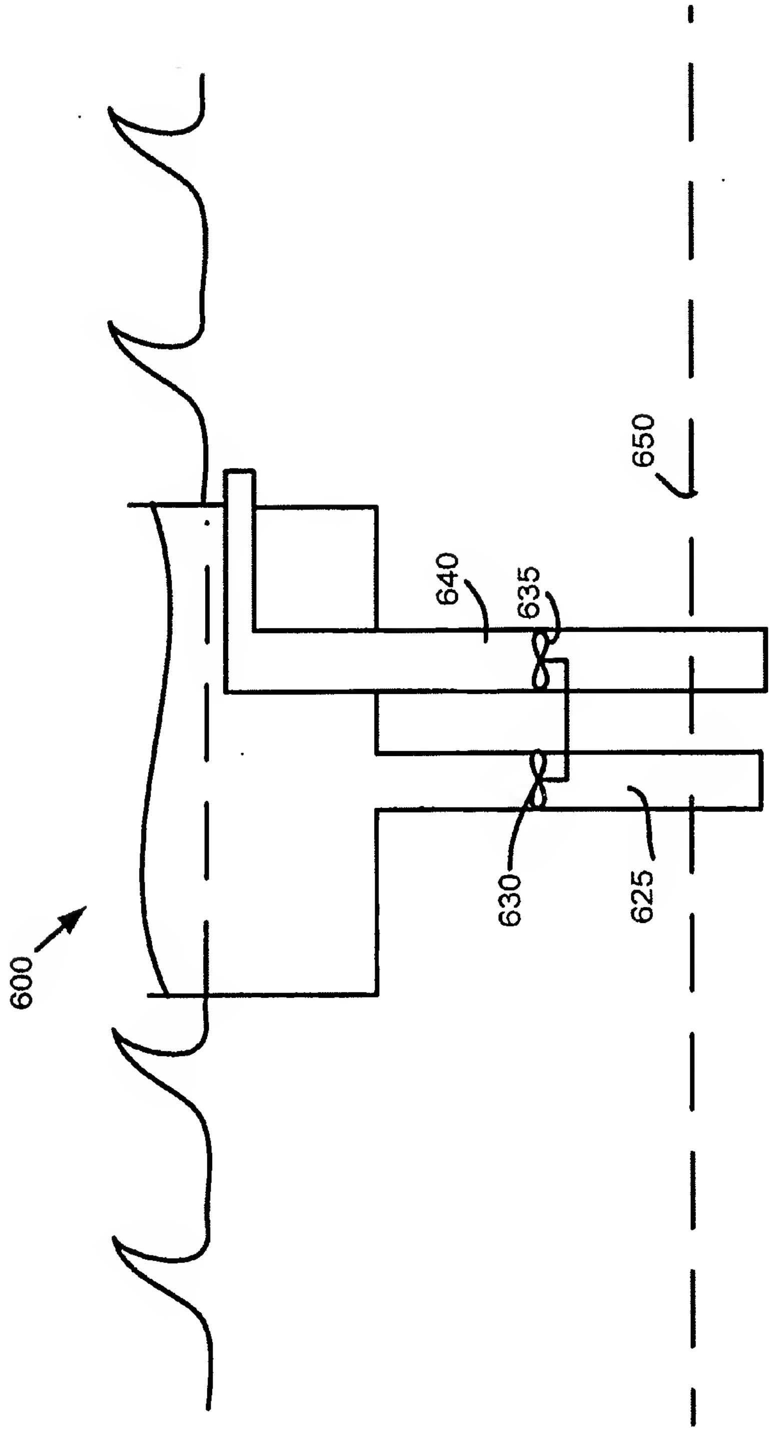


FIG. 7

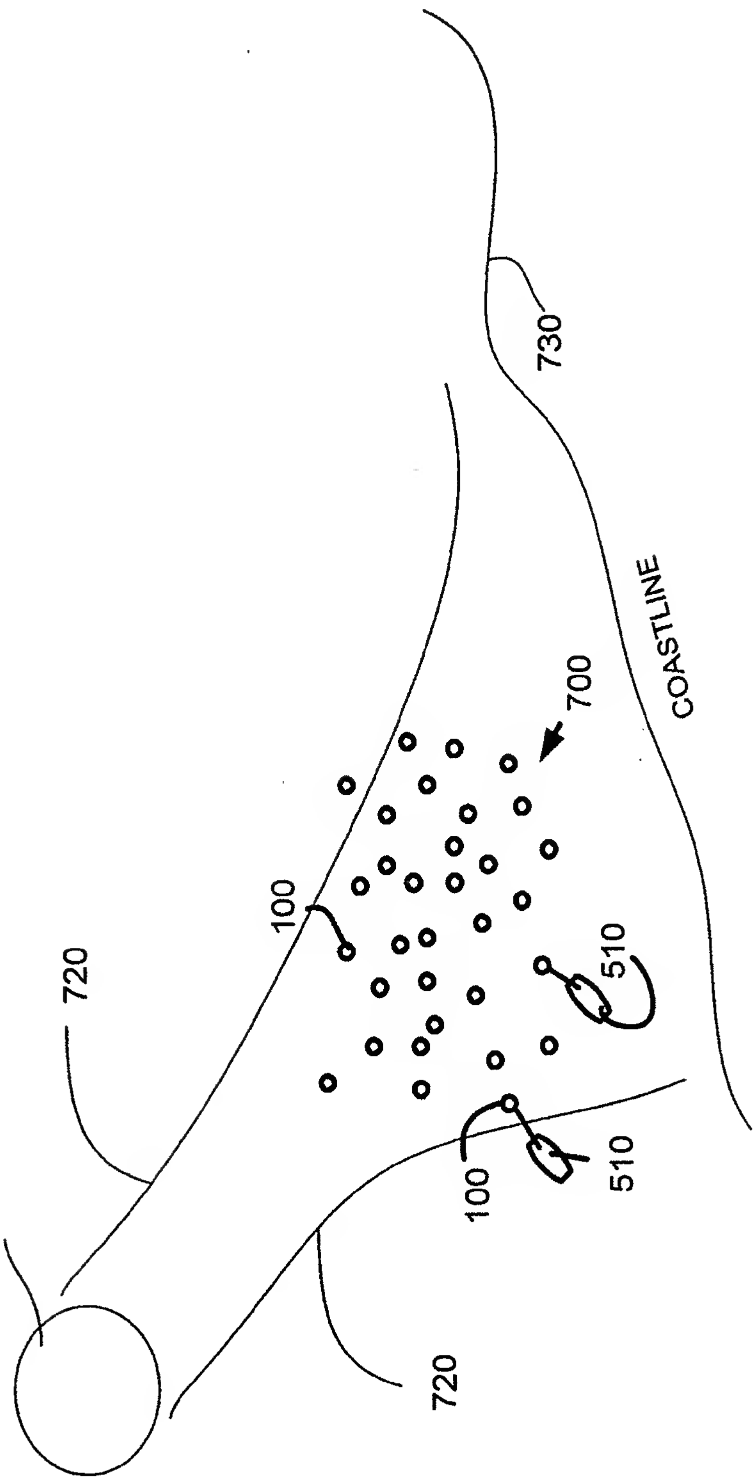


FIG. 8

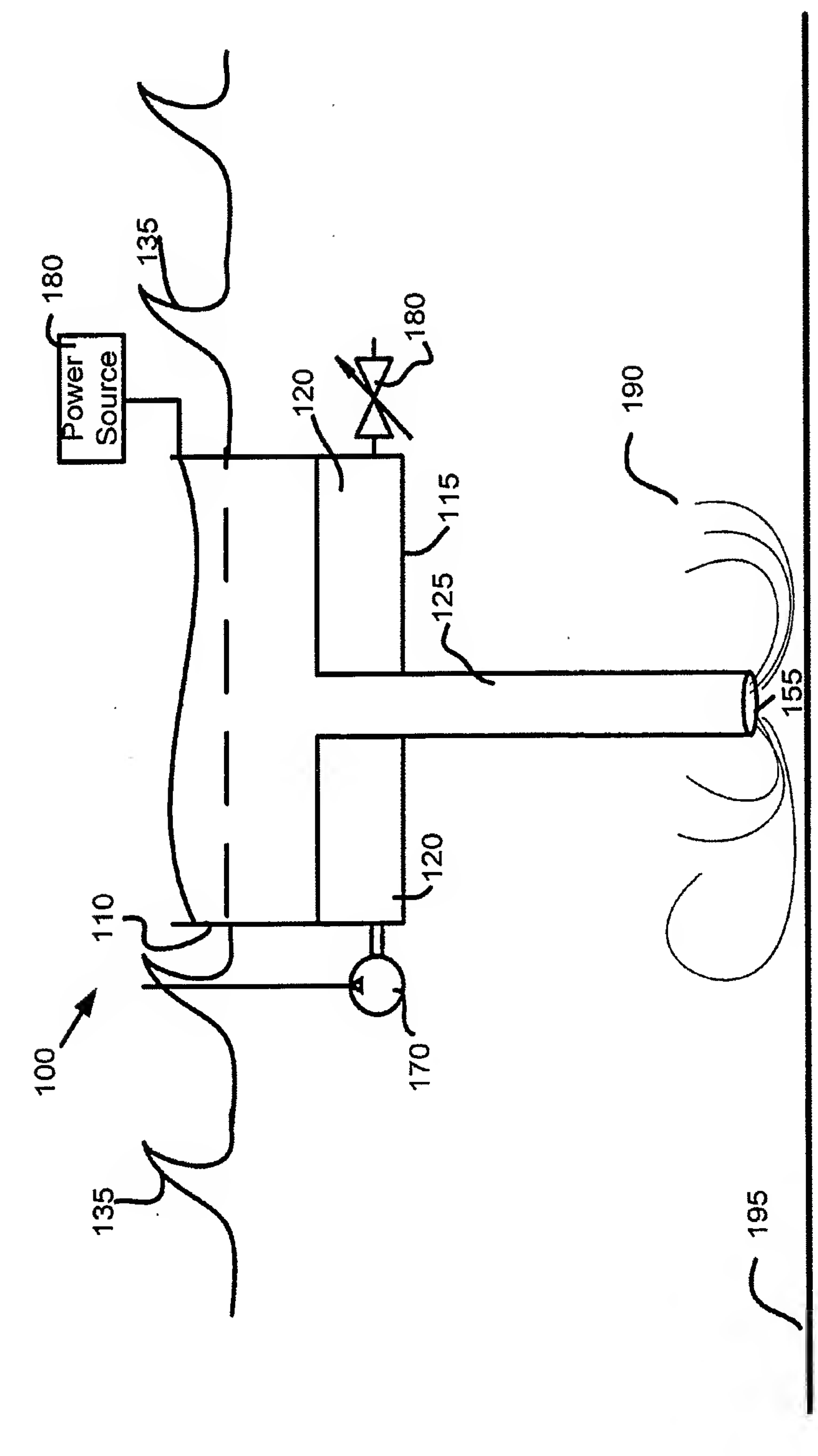

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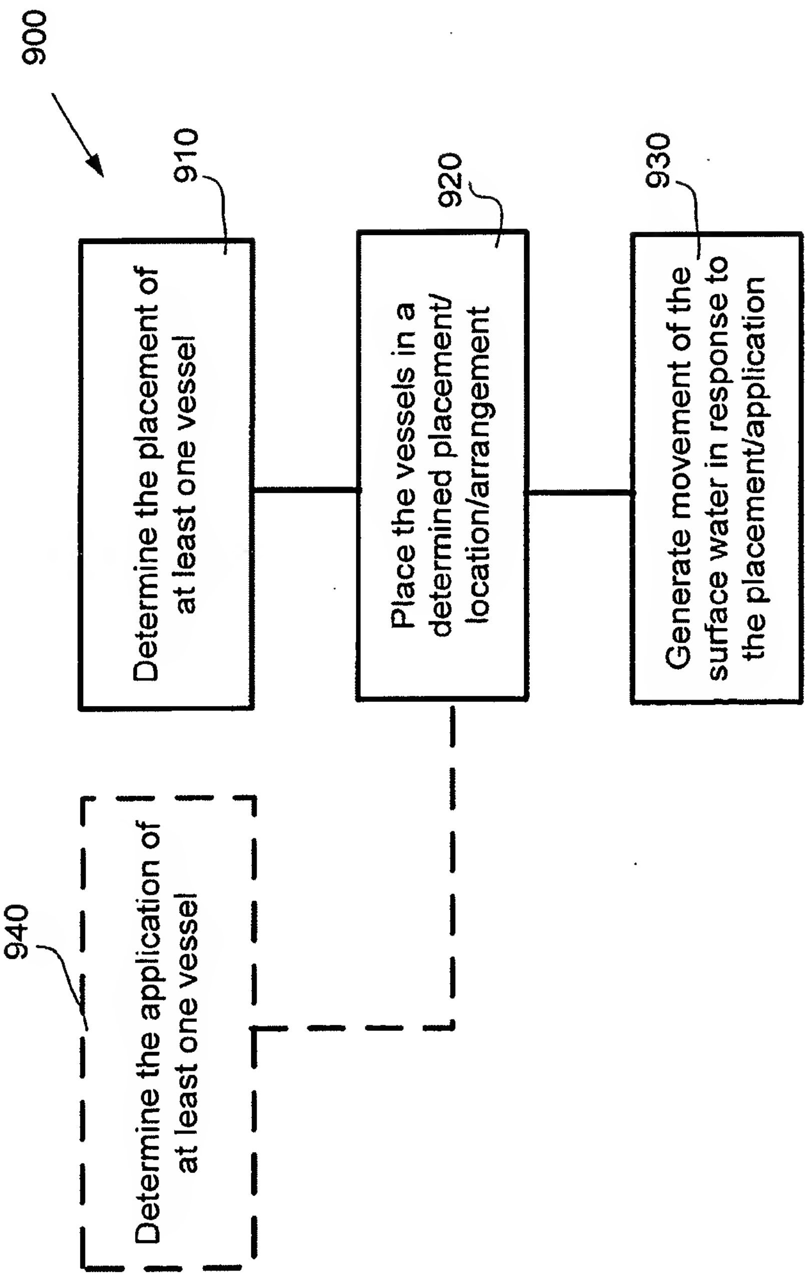
FIG. 9


900
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Determine the placement of at least one vessel
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Place the vessels in a determined placement/ location/arrangement
930
Generate movement of the surface water in response to the placement/application
940
Determine the application of at least one vessel

WATER ALTERATION STRUCTURE APPLICATIONS AND METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application is related to and claims the benefit of the earliest available effective filing date(s) from the following listed application(s) (the "Related Applications") (e.g., claims earliest available priority dates for other than provisional patent applications or claims benefits under 35 USC § 119(e) for provisional patent applications, for any and all parent, grandparent, great-grandparent, etc. applications of the Related Application(s)).

RELATED APPLICATIONS

[0002] For purposes of the USPTO extra-statutory requirements, the preseut application constitutes a continuation-in-part of United States patent application Ser. No. ______, [To Be Assigned by USPTO], entitled WATER ALTERATION STRUCTURE MOVEMENT METHOD AND SYSTEM, naming Jeffrey A. Bowers, Kenneth G Caldeira, Alistair K. Chan, William H. Gates, III, Roderick A. Hyde, Muriel Y. Ishikawa, Jordin T. Kare, John Latham, Nathan P. Myhrvold, Stephen H. Salter, Clarence T. Tegreene, and Lowell L. Wood, Jr. as inventors, filed 3 Jan. 2008, which is currently co-pending, or is an application of which a currently co-pending application is entitled to the benefit of the filing date.

[0003] For purposes of the USPTO extra-statutory requirements, the present application constitutes a continuation-in-part of United States patent application Ser. No. ______, [To Be Assigned by USPTO], entitled WATER ALTERATION STRUCTURE AND SYSTEM, naming Jeffrey A. Bowers, Kenneth G Caldeira, Alistair K. Chan, William H. Gates, III, Roderick A. Hyde, Muriel Y. Ishikawa, Jordin T. Kare, John Latham, Nathan P. Myhrvold, Stephen H. Salter, Clarence T. Tegreene, William H. Wattenburg, Lowell L. Wood, Jr., and Victoria Y. H. Wood as inventors, filed 3 Jan. 2008, which is currently co-pending, or is an application of which a currently co-pending application is entitled to the benefit of the filing date.

[0004] For purposes of the USPTO extra-statutory requirements, the present application constitutes a continuation-in-part of United States patent application Ser. No. ______, [To Be Assigned by USPTO], entitled WATER ALTERATION STRUCTURE RISK MANAGEMENT OR ECOLOGICAL ALTERATION MANAGEMENT SYSTEMS AND METHODS, naming Jeffrey A. Bowers, Kenneth G Caldeira, Alistair K. Chan, William H. Gates, Ill, Roderick A. Hyde, Muriel Y. Ishikawa, Jordin T. Kare, John Latham, Nathan P. Myhrvold, Stephen H. Salter, Clarence T. Tegreene, and Lowell L. Wood as inventors, filed 3 Jan. 2008, which is currently co-pending, or is an application of which a currently co-pending application is entitled to the benefit of the filing date.

[0005] The United States Patent Office (USPTO) has published a notice to the effect that the USPTO's computer programs require that patent applicants reference both a serial number and indicate whether an application is a continuation or continuation-in-part. Stephen G Kunin, Benefit of Prior-Filed Application, USPTO Official Gazette Mar. 18, 2003, available at http://www.uspto.gov/web/offices/com/sol/og/2003/week11/patbene.htm. The preseut Applicant Entity (hereinafter "Applicant") has provided above a specific reference to the application(s) from which priority is being claimed as recited by statute. Applicant understands that the statute is unambiguous in its specific reference language and does not require either a serial number or any characterization, such as "continuation" or "continuation-in-part," for claiming priority to U.S. patent applications. Notwithstanding the foregoing, Applicant understands that the USPTO's computer programs have certain data entry requirements, and hence Applicant is designating the present application as a continuation-in-part of its parent applications as set forth above, but expressly points out that such designations are not to be construed in any way as any type of commentary and/or admission as to whether or not the present application contains any new matter in addition to the matter of its parent application(s).

[0006] All subject matter of the Related Applications and of any and all parent, grandparent, grcat-grandparent, etc. applications of the Related Applications is incorporated herein by reference to the extent such subject matter is not inconsistent herewith.

BACKGROUND

[0007] The description herein generally relates to the field of alteration of water temperatures and dissolved and particulate matter in bodies of water such as oceans, lakes, rivers, structures capable of aiding in the alteration and control of such surface and subsurface water temperatures and compositions as well as the application and methods of application of such structures.

[0008] Conventionally, there is a need for structures for applications related to altering water properties such that there is a diminished contrast between near surface waters and waters found at greater depth, such as but not limited to atmospheric management, weather management, hurricane suppression, hurricane prevention, hurricane intensity modulation, hurricane deflection, biological augmentation, biological remediation, etc. The disclosure relates to methods and systems related to these and other applications.

SUMMARY

[0009] In one aspect, a method of environmental alteration includes determining a placement of at least one vessel capable of moving water to lower depths in the water via wave induced downwelling. The method also includes placing the at least one vessel in the determined placement. Further, the method includes generating movement of the water adjacent the surface of the water in response to the placing.

[0010] In another aspect, a method of environmeutal alteration includes determining an application of at least one vessel capable of moving water to lower depths in the water via wave induced downwelling. The method also includes placing the at least one vessel in the determined placement. Further, the method includes generating movement of the water adjacent the surface of the water based on the application.

[0011] In addition to the foregoing, other method aspects are described in the claims, drawings, and text forming a part of the present disclosure.

[0012] In one or more various aspects, related systems include but are not limited to circuitry and/or programming for effecting the herein-referenced method aspects; the cir-

cuitry and/or programming can be virtually any combination of hardware, software, and/or firmware configured to effect the herein-referenced method aspects depending upon the design choices of the system designer. Also various structural elements may be employed depending on design choices of the system designer.

[0013] In one aspect, a system for altering an aqueous environment includes an application of at least one vessel capable of moving water adjacent the surface of the water via wave induced down welling. The system also includes a system for determining the placement of the at least one vessel based on the application. The system further includes a system for placing the at least one vessel in the determined placement.

[0014] In addition to the foregoing, other system aspects are described in the claims, drawings, and text forming a part of the present disclosure.

[0015] In addition to the foregoing, various other method and/or system and/or program product aspects are set forth and described in the teachings such as text (e.g., claims and/or detailed description) and/or drawings of the present disclosure.

[0016] The foregoing is a summary and thus contains, by necessity, simplifications, generalizations and omissions of detail; consequently, those skilled in the art will appreciate that the summary is illustrative only and is NOT intended to be in any way limiting. Other aspects, features, and advantages of the devices and/or processes and/or other subject matter described herein will become apparent in the teachings set forth herein.

BRIEF DESCRIPTION OF THE FIGURES

[0017] The foregoing summary is illustrative only and is not intended to be in any way limiting. In addition to the illustrative aspects, embodiments, and features described above, further aspects, embodiments, and features will become apparent by reference to the drawings and the following detailed description, of which:

[0018] FIG. 1 is an exemplary diagram of a generalized vessel for holding and moving water.

[0019] FIG. 2 is an exemplary diagram of a pattern of deployment of a plurality of vessels similar to that of FIG. 1.

[0020] FIG. 3 is another exemplary diagram of a pattern of deployment of a plurality of vessels similar to that of FIG. 1.

[0021] FIG. 4 is an exemplary diagram of a generalized vessel for holding and moviug water and depicting on-board propulsive devices.

[0022] FIG. 5 is a simplified depiction of a deployment of a plurality of vessels such as those depicted in FIG. 1 in a geographic region, the simplified depiction not intended to imply any specific scale and the depiction of the vessels and watercraft not drawn to scale.

[0023] FIG. 6 is an exemplary block diagram of a generalized vessel for holding and moving water having an auxiliary conduit.

[0024] FIG. 7 is an exemplary diagram of a storm path with ocean water alteration vessels being placed within a predicted path.

[0025] FIG. 8 is an exemplary diagram of an ocean water alteration vessel being used to cause upheaval and turbulence of material on or adjacent the ocean floor and/or to deliver surface water to areas near the ocean floor.

[0026] FIG. 9 is a process diagram of a method of providing environmental alteration.

DETAILED DESCRIPTION

[0027] In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented here. Those having skill in the art will recognize that the state of the art has progressed to the point where there is little distinction left between hardware and software implementations of aspects of systems; the use of hardware or software is generally (but not always, in that in certain contexts the choice between hardware and software can become significant) a design choice representing cost vs. efficiency tradeoffs. Those having skill in the art will appreciate that there are various vehicles by which processes and/or systems and/or other technologies described herein can be effected (e.g., hardware, software, and/or firmware), and that the preferred vehicle will vary with the context in which the processes and/or systems and/or other technologies are deployed. For example, if an implementer determines that speed and accuracy are paramount, the implementer may opt for a mainly hardware and/or firmware vehicle; alternatively, if flexibility is paramount, the implementer may opt for a mainly software implementation; or, yet again alternatively, the implementer may opt for some combination of hardware, software, and/or firmware. Hence, there are several possible vehicles by which the processes and/or devices and/or other technologies described herein may be effected, none of which is inherently superior to the other in that any vehicle to be utilized is a choice dependent upon the context in which the vehicle will be deployed and the specific concerns (e.g., speed, flexibility, or predictability) of the implementer, any of which may vary. Those skilled in the art will recognize that optical aspects of implementations will typically employ optically-oriented hardware, software, and or firmware.

[0028] The foregoing detailed description has set forth various embodiments of the devices and/or processes via the use of block diagrams, flowcharts, and/or examples. Insofar as such block diagrams, flowcharts, and/or examples contain one or more functions and/or operations, it will be understood by those within the art that each function and/or operation within such block diagrams, flowcharts, or examples can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, or virtually any combination thereof. In one embodiment, several portions of the subject matter described herein may be implemented via Application Specific Integrated Circuits (ASICs), Field Programmable Gate Arrays (FPGAs), digital signal processors (DSPs), or other integrated formats. However, those skilled in the art will recognize that some aspects of the embodiments disclosed herein, in whole or in part, can be equivalently implemented in integrated circuits, as one or more computer programs running on one or more computers (e.g., as one or more programs running on one or more computer systems), as one or more programs running on one or more processors (e.g., as one or more programs running on one or more microprocessors), as firmware, or as virtually any combination thereof, and that designing the circuitry and/or writing the

code for the software and or firmware would be well within the skill of one of skill in the art in light of this disclosure. In addition, those skilled in the art will appreciate that the mechanisms of the subject matter described herein are capable of being distributed as a program product in a variety of forms, and that an illustrative embodiment of the subject matter described herein applies regardless of the particular type of signal bearing medium used to actually carry out the distribution. Examples of a signal bearing medium include, but are not limited to, the following: a recordable type medium such as a floppy disk, a hard disk drive, a Compact Disc (CD), a Digital Video Disk (DVD), a digital tape, a computer memory, etc.; and a transmission type medium such as a digital and/or an analog communication medium (e.g., a fiber optic cable, a waveguide, a wired communications link, a wireless communication link, etc.). Further, those skilled in the art will recognize that the mechanical structures disclosed are exemplary structures and many other forms and materials may be employed in constructing such structures.

[0029] The need for mechanisms, devices, methods, systems, and structures which may be used to alter hurricanes either in their strength, their origin, or their direction of travel has been realized. Billions of dollars of destruction and damage is regularly attributable to hurricanes and hurricane-like tropical storms. Thus, great interest has arisen in controlling these powerful storms. Conventionally, it has been proposed to deploy barges equipped with upward-pointing jet engines into the paths of hurricanes. The jet engines would theoretically be configured to create mini-cyclones which would consume oceanic energy and thus prevent or suppress such high powered weather systems.

[0030] Another potential solution involves the use of Dyn-O-Gel, a polymer that may absorb as much as 1,500 times its own weight in water to deprive a hurricane of atmospheric moisture. The concept involves the use of airplanes to drop Dyno-O-Gel into hurricanes to deprive them of moisture and thus of latent heat. The powder is suggested to convert into a gel when the atmospheric moisture is captured and would then reliquify when it encounters higher-osmolality ocean water.

[0031] The jet engine solution has been met with great skepticism and the cost and feasibility are very uncertain. The use of a moisture absorbing gel requires the deployment of a huge volume of the absorbing gel material. Also, the use of a moisture absorbing material is still in the testing phase. The gel material after absorbing moisture falls to the ocean and may dissolve. Depending on the chemical composition of the gel, the gel be regarded as a pollutant. These various shortcomings considered, it may be desirable to provide a different approach for altering hurricane and/or tropical storm activity by providing a structure and method that solves at least one or more deficiencies of other systems known in the art. Because hurricanes and other tropical storms derive their energy from warm ocean water, it is logical to harness the great energies of the Earth's fluid envelopes to suppress or alter hurricanes or other tropical storms, and/or to employ the powers of motion within these envelopes over long time-intervals to modulate at least one property of an envelope that is exploited over much shorter time-scales and/or much more limited spatial scales for energizing a hurricane.

[0032] A potential solution for cooling warm surface water has been explored by researchers with Atmocean, Inc. of Santa Fe, N. Mex. In the Atmocean approach, an elongated tube with a buoy is used to create an upwelling effect. The upwelling effect drives cold water from a depth to the surface.

[0033] It is well known that a hurricane's primary energy source is the release of the heat of condensation of water vapor condensing at high altitudes, with solar-derived heat being the initial source for evaporation. Therefore, a hurricane may be seen as a giant vertical heat engine, albeit one dependent upon mass supplied by largely horizontal flows. Water condensation leads to higher wind speeds, as a fraction of the released energy is converted immediately into thermal energy and thence into mechanical energy, the faster winds and lower pressures associated with them in turn cause increased surface evaporation and thus even more subsequent condensation. Much of the released energy drives updrafts that increase the height of speeding up condensation. This gives rise to factors that provide the system with enough energy to be self-sustaining, and result in a positive feedback loop that continues as long as the tropical cyclone can draw energy from a thermal reservoir and isn't excessively sheared along its vertical extent. In this case, the heat source is the warm water at the surface of the ocean. Without this thermal reservoir to support it a hurricane or other similar storm will not commence, will be weaker, or will die out as the positive feedback loop diminishes to sub-threshold levels or never gets above them.

[0034] Referring now to FIG. 1, a cross-section of a water-borne structure or vessel **100** is depicted. Vessel **100** is a tub-like structure having one or more walls **110** and a bottom **115**. Vessel **100** may be held buoyant in the water by one or more buoyancy tanks **120** which may be used to maintain the buoyancy of vessel **100** and further may be used to control the height of walls **110** above the water level. Vessel **100** also includes a conduit **125** whose horizontal cross section is substantially smaller than the horizontal cross section of the tub portion **130** of the vessel defined by walls **110**. In an exemplary embodiment, conduit **125** extends well below the ocean surface including depths below the ocean's thermocline.

[0035] In most circumstances, most of the sunlight impinging on the ocean surface is absorbed in the surface layer. The surface layer therefore heats up. Wind and waves move water in this surface layer which distributes heat within it. The temperature may therefore be reasonably uniform to depths extending a few hundred feet down from the ocean surface. Below this mixed layer, however, the temperature decreases rapidly with depth, for example, as much as 20 degrees Celsius with an additional 150 m (500 ft) of depth. This area of rapid transition is called the thermocline. Below it, the temperature continues to decrease with depth, but far more gradually. In the Earth's oceans, approximately 90% of the mass of water is below the thermocline. This deep ocean consists of layers of substantially equal density, being poorly mixed, and may be as cold as −2 to 3° C.

[0036] Therefore, the lower depths of the ocean may be used as a huge heat/energy sink which may be exploited by vessel **100**. When vessel **100** is deployed at sea, waves **135** may lap over the top of walls **110** to input warm (relative to deeper waters) surface ocean water into tub **130**. Tub **130** will fill to a level **140** which is above the average ocean level depicted as level **145**. Because of the difference between levels **140** and **145**, a pressure head is created thereby pushing warm surface ocean water in a downward direction **150** down through conduit **125** to exit into the cold ocean depths (relative to near surface waters) through one or more openings

155. In an exemplary embodiment, the depth of opening 155 may be located below the ocean's thermocline, the approximate bottom of which is depicted as line 160. This cycle will be continuous in bringing warm surface ocean water to great depth as ocean waves continue to input water into tub 130.

[0037] If many of vessel 100 are distributed throughout a region of water, the temperature of the surface of the water may be altered. Referring to FIG. 2, an array 200 of vessels 100 is depicted. Such vessels may be arranged in a plurality of ways, including but not limited to positioning them in a water region in an array, such as array 200, in a random placement 300, as depicted in FIG. 3, within a region, and/or in any other arrangement. It may be desirable to determine the most suitable and/or optimal arrangements through computer modeling or other techniques. Referring now to FIG. 5, it may be seen that many vessels 100 may be dispersed throughout hurricane prone regions such as but not limited to the Gulf of Mexico 500 or the Caribbean Sea. Vessels 100, depicted for illustrative purposes only and not to scale are shown being dispersed in a relatively random pattern. Boats 510 may be used to tow vessels to desired locations. Also, other means such as self propulsion, airlifting, towing, or other methods to move vessels may also be used. In another embodiment, vessels 100 may be anchored in a variety of ways, including but not limited to anchored to the bottom, anchored using subsurface weights, anchored using sea anchors, or anchored to each other.

[0038] Referring now to FIG. 7, a group 700 of holding vessels 100 is depicted in a path, approximately defined by lines 720, of a storm 710. Storm 710 may include many of a variety of atmospheric or oceanic disturbances, such as but not limited to a tropical depression, a tropical storm, a low pressure atmospheric disturbance, a predicted storm, a hurricane, or a typhoon (tropical cyclone). As described above, such disturbances derive energy from warm surface water, therefore by producing a change in the surface temperature of the oceanic region within a path 720 of the storm 710, storm 710 may be affected by being diminished in energy, by being deflected, by being destroyed, etc. Through weather prediction techniques, the path 720 of disturbance 710 may be determined and vessels 100 may be moved into the path 720 of storm 710 by using watercraft 510 (or by using other techniques) to move vessels 100 into desired placements or positions. In one exemplary embodiment, coastline 730 may be desired to be protected. Coastline 730 may include beaches, coral reefs, atolls, islands, communities, buildings, etc. which may be desired to be protected from strong storms, winds, storm surges, aud the like.

[0039] Referring again to FIG. 1 vessel 100 may be one vessel in a system for altering water surface temperature. As such the tub 130 is one type of a holdiug vessel configured to hold water. Tub 130 includes at least one wall 110 (but may include multiple walls) which are coupled to a bottom portion 115. The at least one wall 110 extends above the water level and the bottom portion 115 is configured to be submerged. At least one conduit 125 extends from the bottom of the tub 130. In some, but not necessarily all, applications, it may be desirable for conduit 125 to have a length that extends to a depth at which the temperature of water at the depth (e.g., below line 160) is substantially less than water at the surface.

[0040] Vessel 100 may be held buoyant by both the materials used to construct vessel 100 as well as at least one ballast tank 120. Tanks 120 may be coupled to at least one pump 170 and at least one valve 180. In accordance with an exemplary embodiment, the height of wall 110 above the average water surface level may be varied and controlled depending ou the time-varying height of the local waves and depending on the desired flow rate through conduit 125. One way in which to vary the height of wall 110 above the average water level 145 is to pump atmospheric air into tank 120 or out of tank 120. In conjunction with pump 170, valve 180 may be used to draw water into or out of tanks 120. In accordance with another exemplary embodiment, it may be desirable to have the ability to mechanically raise or lower at least a portion of wall 110 relative to the rest of the structure. It may also be desirable to control the raising and lowering of all or part of wall 110 in response to conditions adjacent to vessel 100 (e.g., water temperature, wave height).

[0041] In another embodiment, water flow into vessel 100 may be via openings 175 in wall 110, rather than over the top of wall 110. Such openings may be configured to preferentially allow flow into vessel 100, instead of out of the vessel. In some embodiments, openings 175 are passive, using flaps, checkvalves, rotating drums, or similar mechanisms to support unidirectional flow. In other embodiments, openings 175 are actively controlled, utilizing motorized or variable setpoint flow control devices such as valves, flaps, rotating drums, or similar mechanisms.

[0042] Walls 110 and bottom portion 115 as well as other parts of vessel 100 may be constructed of any of a variety of materials and preferably of a material substantially resistant to degradation in water. For example, vessel 110 may be substantially constructed from concrete, polymers, at least one of metals or metal alloys, fabrics, reinforced fabrics, and/or composite materials. In some applications, it may be advantageous for the construction materials to resist degradation only for a limited period of time, as degradation of the structure may diminish or eliminate expenditures associated with post-application retrieval of the structure. Furthermore, it may be advantageous to allow the structure to sink below the water surface or to the water bottom after application, where degradation may be preferred to occur. In an exemplary embodiment, conduit 125 may be formed of any of a variety of materials including both rigid materials and flexible materials. It may also be desirable to use stiffening structures in the conduit depending on the type of materials used. Such stiffening structures aid in maintaiuing the shape of couduit 125 under pressure and under stress. The stiffening structures may be placed at one or more locations along the length of the conduit. Further, such stiffening structures may be deployable and may aid in deployment along with a conduit which may also be deployable from tub 130. In yet another exemplary embodiment, it may be desirable to form vessel 100 from a material which would be known to degrade over time. This may be useful if it is known that a vessel has a desired lifespan or term of usefulness. Once the vessel's use is done, the vessel could sink or be sunk where it could subsequently degrade at a subsurface location.

[0043] In an exemplary embodiment the holding vessel or tub 110 has a horizontal cross sectional dimension that is substantially greater than a horizontal cross sectional dimension of the conduit 125. In another exemplary embodiment holding vessel or tub 100 has a horizontal cross sectional dimension and/or shape that is substantially the same as the cross sectional dimension and/or shape as conduit 125. The pressure head created by the weight of the column of water above the conduit which is above the line 145 is used to pressurize the descending water in conduit 125. In an exem-

plary embodiment it may be convenient to have a power source **190** on board vessel **100**. Power source **190** may be any of a variety of power sources, including but not limited to a solar cell, a wind generator, a wave power generator, a turbine turned by water descending in the conduit, a battery power source, a fuel powered power source, a thermoelectric power source, etc.

[0044] In accordance with an exemplary embodiment a vessel **600** is depicted in FIG. **6** having a conduit **625**. Disposed within conduit **625** is a turbine **630**. Turbine **630** may be driven by the flow of water through conduit **625**. Turbine **630** may be utilized for a variety of purposes including but not limited to generating power for a variety of purposes, maintaining buoyancy, controlling buoyancy, driving other turbines, increasing the water flow through conduit **625**, etc.

[0045] In accordance with other exemplary embodiments it may be desirable to equip vessel **100** with one or more propulsion systems. Referring now to FIG. **4**, a propulsion system may be in the form of a sail or a propeller **450** or other motorized propulsion producing device. Such a propulsive device may be powered by power source **460** or any other source of power. The propulsion system may be used to control the positioning of vessel **100** such that it remains at a specific area, moves in a specific pattern, and/or moves to a completely new location. A rudder **470**, fin, sail, or other steering device may be coupled to vessel **100** to help guide vessel **100**. Alternatively, a sail or a propeller **450** may be configured to change orientation to provide steering for vessel **100**. Because different depths in bodies of water often have currents flowing in different directions or with different speeds, a propulsion system may involve the use of one or more sea anchors with mechanisms and control systems to effect proper placement of the sea anchors. In one exemplary embodiment, it may be desirable to construct vessel **100** with a shape such that its coefficient of drag is less in one direction than another. This may be accomplished by making the dimensions of vessel **100** longer in one direction than another, for example. Other methods and shapes may also be used to produce such an effect.

[0046] In accordance with another exemplary embodiment, vessel **100** may include a movable conduit in which at least a portion **480** of conduit **425** may be movable in various directions in order to provide a propulsive force in a desired direction. In another exemplary embodiment, the movable portion may be one or more openings which may be controlled, along the length of conduit **425**. The propulsive force generated by water flow through conduit **425** may also be varied by opening and closing opening **485** using a controlled access device such as door **490** (or other aperture control devices such as but not limited to valves, etc.) that may control the flow rate through conduit **425**. In one exemplary embodiment the walls of conduit **425** may be movable in a deformable manner thereby being capable of creating a peristaltic motion in conduit **425** and providing the capability of increasing the flow rate through conduit **425**.

[0047] In an exemplary embodiment walls **410** of vessel **100** may be formed of multiple wall segments or multiple wall portions. The multiple wall segments of walls **410** form a closed shape to contain water within vessel **100**. The wall segments may be curved or straight, may be movable in such a way as to help let in water or alternatively to release water. In one exemplary embodiment, vessel **100** may be permanently anchored to the water floor, temporarily anchored to the water floor, tied to a subsurface weight, tied to one or more sea-anchors, or may be freely movable. In one exemplary embodiment, vessel **100** is movable by coupling the vessel to a propulsive vessel, such as a tugboat or the like. In another exemplary embodiment, vessel **100** may include a wind capture structure, such as a sail **495** that may be used to harness wind power for moving the holding vessel. The wind capture structure may be used for controlling the amount that the at least one wall of the holding vessel extends above the water, that is it may also be used to provide lift to the holding vessel **100** structure, to help control how far above the water level that walls **410** extend. Sea anchors are functionally similar to sails, except instead of extending up into the atmosphere they are deployed into the water. Thus, sea auchors or current capture structures may be used for similar purposes as sails and wind capture structures. These include moving or holding the vehicle, generating power, providing lift, etc. Also in an exemplary embodiment, vessel **100** may have a ramp area **475** or other wave altering area that helps to control how the waves move water over the sides of vessel **100**. This wave-altering structure may be a static or passive structure, or it may be an active device or structure having one or more components that are actuated or powered in order to have a time-dependent character or activity; the power for such purposes may be derived from any of the power-providing means discussed above, or may be derived from the wave-action itself. Further, in an exemplary embodiment, vessel **100** may have any of a variety of shapes including but not limited to circular, elongated, non-circular, shaped in a manner which aids in passively controlling orientation relative to wave motion, etc.

[0048] Referring now to FIG. **6**, a vessel **600** is depicted. Vessel **600** includes a conduit **625** in which a turbine **630** is driven by the downward flow of water through conduit **625**. In an exemplary embodiment, the turning turbine may be used for a variety of purposes including providing power, providing control, providing propulsive power, etc. In one exemplary embodiment a secondary conduit **640** (which represents one or more conduits) may be used to bring cold ocean water (such as below thermocline **650**) to upper areas of warmer surface water to aid in cooling the warm surface water regions. In one exemplary embodiment, turbine **630** may be used to drive a second turbine **635** in conduit **640** that pumps water up through conduit **640**. Further, other mechanisms may be used to bring subsurface water upwards. In most places, deeper waters contain a greater concentration of nutrients than surface water, so conduit **640** may also be used to transport dissolved nutrients from deeper waters to waters near the surface of the body of water. Referring now to FIG. **8**, a vessel **100** as depicted in FIG. **1** is depicted having conduit **125** outlet **155** adjacent the floor **195** of a body of water (ocean, lake, sea, etc.). Water flowing out of outlet **155** may be used to cause turbidity near floor **195** by stirring up sediment from the bottom. Some of this sediment may include food or other nutrients which may encourage plant and animal growth. Also, nutrients and warm water may be brought from the surface also aiding in stimulating plant and animal growth. Thus, by the placement of one or more vessels **100** in a particular location, plant and animal life may be encouraged. This may be used for developing wildlife preservation areas, wildlife recreation areas, restoring wildlife destroyed by natural or man-made causes, etc.

[0049] Referring now to FIG. **9**, a method **900** of environmental alteration includes determining a placement of at least one vessel capable of moving water adjacent the surface of the water to a lower depth in the water (process **910**). The method

also includes placing the at least one vessel in the determined placement, location, and/or arrangement (process **920**). Further, the method includes generating movement of the water adjacent the surface of the water in response to the placing (process **930**). The movement is caused once a sufficient pressure head has been developed to cause a downward flow of surface waters through the conduit of the water alteration vessel. In accordance with an alternative embodiment, a method of environmental alteration includes determining an application of at least one vessel that is capable of moving water adjacent the surface of the water to a lower depth in the water primarily using a developed pressure head in the vessel (process **940**). The method also includes placing the at least one vessel in the determined placement (process **920**) and generating movement of the water adjacent the surface of the water based on the application (process **930**).

[0050] The capability of the systems and methods described to enhance mixing between surface and subsurface water can be useful for other applications in addition to thermally based weather modification. One such application is to aid in ocean uptake of atmospheric CO2. Oceans are natural CO2 sinks, and represent the largest active carbon sink on Earth. This role as a sink for CO2 is driven by two processes, the solubility pump and the biological pump. The former is primarily a function of differential CO2 solubility in seawater and the thermohaline circulation, while the latter is the sum of a series of biological processes that transport carbon (in organic and inorganic forms) from the near-surface euphotic zone to the ocean's interior.

[0051] The solubility pump is a nonbiological effect wherein CO2 first dissolves in the surface layer of the ocean. This surface layer can become saturated and its ability to absorb more carbon dioxide declines. Use of this system to promote mixing between surface and subsurface water enhances the efficacy of solubility pump in at least two manners; by net transport of CO2-enriched water downwards, as well as by reducing the temperature of the surface water, thereby increasing its ability to dissolve CO2. The solubility pump enhancement induced by this system can also be useful for increasing ocean uptake of other atmospheric gases, such as methane, nitrogen oxides, sulfur dioxide, etc.

[0052] While the biological pump currently has a limited effect on uptake of CO2 introduced into the atmosphere by human activities, there have been suggestions to increase the carbon sequestration efficiency of the oceans by increasing the surface-layer phytoplankton concentration, which is in many instances limited by insufficient surface-layer nutrients. Nitrates, silicates, and phosphates are, for instance, largely absent from surface waters, yet are considerably more abundant in subsurface oceans. These exemplary systems and methods can be used to mix surface and subsurface waters, thereby transporting nutrients towards the surface. This increase in surface nutrients can be useful in increasing the CO2 biological pump by increasing surface-layer phytoplankton concentrations. Increases in surface-layer nutrients can also be useful for increasing populations of water-based fauna or flora, both in oceans and in other water bodies, such as lakes, reservoirs, rivers, etc.

[0053] The benefits of these systems and methods in increasing mixing between surface and subsurface water is not restricted to use in oceans, but can also be beneficial in other bodies of water, such as lakes, reservoirs, rivers, etc.

[0054] In a general sense, those skilled in the art will recognize that the various embodiments described herein can be implemented, individually and/or collectively, by various types of electro-mechanical systems having a wide range of electrical components such as hardware, software, firmware, or virtually any combination thereof; and a wide range of components that may impart mechanical force or motion such as rigid bodies, spring or torsional bodies, hydraulics, and electro-magnetically actuated devices, or virtually any combination thereof. Consequently, as used herein "electro-mechanical system" includes, but is not limited to, electrical circuitry operably coupled with a transducer (e.g., an actuator, a motor, a piezoelectric crystal, etc.), electrical circuitry having at least one discrete electrical circuit, electrical circuitry having at least one integrated circuit, electrical circuitry having at least one application specific integrated circuit, electrical circuitry forming a general purpose computing device configured by a computer program (e.g., a general purpose computer configured by a computer program which at least partially carries out processes and/or devices described herein, or a microprocessor configured by a computer program which at least partially carries out processes and/or devices described herein), electrical circuitry forming a memory device (e.g., forms of random access memory), electrical circuitry forming a communications device (e.g., a modem, communications switch, or optical-electrical equipment), and any non-electrical analog thereto, such as optical or other analogs. Those skilled in the art will also appreciate that examples of electro-mechanical systems include but are not limited to a variety of consumer electronics systems, as well as other systems such as motorized transport systems, factory automation systems, security systems, and communication/computing systems. Those skilled in the art will recognize that electro-mechanical as used herein is not necessarily limited to a system that has both electrical and mechanical actuation except as context may dictate otherwise.

[0055] In a general sense, those skilled in the art will recognize that the various aspects described herein which can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, or any combination thereof can be viewed as being composed of various types of "electrical circuitry." Consequently, as used herein "electrical circuitry" includes, but is not limited to, electrical circuitry having at least one discrete electrical circuit, electrical circuitry having at least one integrated circuit, electrical circuitry having at least one application specific integrated circuit, electrical circuitry forming a general purpose computing device configured by a computer program (e.g., a general purpose computer configured by a computer program which at least partially carries out processes and/or devices described herein, or a microprocessor configured by a computer program which at least partially carries out processes and/or devices described herein), electrical circuitry forming a memory device (e.g., forms of random access memory), and/or electrical circuitry forming a communications device (e.g., a modem, communications switch, or optical-electrical equipment). Those having skill in the art will recognize that the subject matter described herein may be implemented in an analog or digital fashion or some combination thereof.

[0056] Those skilled in the art will recognize that it is common within the art to implement devices and/or processes and/or systems in the fashion(s) set forth herein, and thereafter use engineering and/or business practices to integrate such implemented devices and/or processes and/or systems into more comprehensive devices and/or processes and/or sys-

tems. That is, at least a portion of the devices and/or processes and/or systems described herein can be integrated into other devices and/or processes and/or systems via a reasonable amount of experimentation. Those having skill in the art will recognize that examples of such other devices and/or processes and/or systems might include—as appropriate to context and application—all or part of devices and/or processes and/or systems of (a) an air conveyance (e.g., an airplane, rocket, hovercraft, helicopter, etc.), (b) a ground conveyance (e.g., a car, truck, locomotive, tank, armored personnel carrier, etc.), (c) a building (e.g., a home, warehouse, office, etc.), (d) an appliance (e.g., a refrigerator, a washing machine, a dryer, etc.), (e) a communications system (e.g., a networked system, a telephone system, a Voice over IP system, etc.), (f) a business entity (e.g., an Internet Service Provider (ISP) entity such as Comcast Cable, Quest, Southwestern Bell, etc), or (g) a wired/wireless services entity such as Sprint, Cingular, Nextel, etc.), etc.

[0057] One skilled in the art will recognize that the herein described components (e.g., steps), devices, and objects and the discussion accompanying them are used as examples for the sake of conceptual clarity and that various configuration modifications are within the skill of those in the art. Consequently, as used herein, the specific exemplars set forth and the accompanying discussion are intended to be representative of their more general classes. In general, use of any specific exemplar herein is also intended to be representative of its class, and the non-inclusion of such specific components (e.g., steps), devices, and objects herein should not be taken as indicating that limitation is desired.

[0058] With respect to the use of substantially any plural and/or singular terms herein, those having skill in the art can translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations are not expressly set forth herein for sake of clarity.

[0059] The herein described subject matter sometimes illustrates different components contained within, or connected with, different other components. It is to be understood that such depicted architectures are merely exemplary, and that in fact many other architectures can be implemented which achieve the same functionality. In a conceptual sense, any arrangement of components to achieve the same functionality is effectively "associated" such that the desired functionality is achieved. Hence, any two components herein combined to achieve a particular functionality can be seen as "associated with" each other such that the desired functionality is achieved, irrespective of architectures or intermedial components. Likewise, any two components so associated can also be viewed as being "operably connected", or "operably coupled", to each other to achieve the desired functionality, and any two components capable of being so associated can also be viewed as being "operably couplable", to each other to achieve the desired functionality. Specific examples of operably couplable include but are not limited to physically mateable and/or physically interacting components and/or wirelessly interactable and/or wirelessly interacting components and/or logically interacting and/or logically interactable components.

[0060] While particular aspects of the present subject matter described herein have been shown and described, it will be apparent to those skilled in the art that, based upon the teachings herein, changes and modifications may be made without departing from the subject matter described herein and its broader aspects and, therefore, the appended claims are to encompass within their scope all such changes and modifications as are within the true spirit and scope of the subject matter described herein. Furthermore, it is to be understood that the invention is defined by the appended claims. It will be understood by those within the art that, in general, terms used herein, and especially in the appended claims (e.g., bodies of the appended claims) are generally intended as "open" terms (e.g., the term "including" should be interpreted as "including but not limited to," the term "having" should be interpreted as "having at least," the term "includes" should be interpreted as "includes but is not limited to," etc.). It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases "at least one" and "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to inventions containing only one such recitation, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an" (e.g., "a" and/or "an" should typically be interpreted to mean "at least one" or "one or more"); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation is explicitly recited, those skilled in the art will recognize that such recitation should typically be interpreted to mean at least the recited number (e.g., the bare recitation of "two recitations," without other modifiers, typically means at least two recitations, or two or more recitations). Furthermore, in those instances where a convention analogous to "at least one of A, B, and C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, and C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). In those instances where a convention analogous to "at least one of A, B, or C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, or C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). It will be further understood by those within the art that virtually any disjunctive word and/or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase "A or B" will be understood to include the possibilities of "A" or "B" or "A and B."

[0061] While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

1. A method of environmental alteration, comprising:

determining a placement of at least one vessel capable of moving water to lower depths in the water via wave induced downwelling;

placing the at least one vessel in the determined placement; and

generating movement of the water adjacent the surface of the water in response to the placing.

2. The method of claim 1, wherein the determining a placement includes predicting the path of at least one of a tropical depression, a tropical storm, a low pressure atmospheric disturbance, a predicted storm, a hurricane, or a typhoon.

3. The method of claim 1, wherein the placing the at least one vessel includes adding additional vessels to a group of vessels.

4. The method of claim 1, wherein the placing the at least one vessel includes moving the vessels by watercraft.

5. The method of claim 1, wherein the placing the at least one vessel includes moving the vessels by controlling a propulsion device operatively coupled to the vessels.

6. The method of claim 1, wherein the generating movement includes controlliug the rate of movement of water.

7. The method of claim 1, wherein the determining includes placing the at least one vessel over or in an area in which biological augmentation is desired.

8. The method of claim 1, wherein the determining includes placing the at least one vessel over or in an area in which biological destruction is desired.

9. The method of claim 1, further comprising:

creating an area of biological interest.

10. The method of claim 1, further comprising:

creating an area of interest for recreational observance.

11. The method of claim 1, wherein the placing the at least one vessel includes positioning the vessels to protect beach areas from being damaged by storms.

12. The method of claim 1, wherein the at least one vessel comprises a tub portion configured to hold water, the tub portion having at least one wall coupled to a bottom portion, the at least one wall extending above the water level and the bottom portion configured to be submerged.

13. The method of claim 1, further comprising:

interconnecting one or more vessels.

14. The method of claim 1, further comprising:

anchoring at least one vessel to the bottom of a water body or anchoring at least one vessel to a sea anchor.

15. The method of claim 1, further comprising:

connecting at least one vessel to an external structure.

16. The method of claim 1, wherein at least one vessel comprises at least one conduit extending from a bottom of the at least one vessel, the at least one conduit having a length extending to a depth below the bottom.

17. The method of claim 1, further comprising:

creating an area of meteorological interest.

18. The method of claim 1, further comprising:

generating movement of the water at depths below the surface of the water in response to the placing.

19. A system for altering an aqueous environment, comprising:

an application of at least one vessel capable of moving water to lower depths in the water via wave induced downwelling;

a system for determining the placement of the at least one vessel based on the application; and

a system for placing the at least one vessel in the determined placement.

20. The system of claim 19, wherein the at least one vessel comprises a tub portion configured to hold water, the tub portion having at least one wall coupled to a bottom portion, the at least one wall extending above the water level and the bottom portion configured to be submerged.

21. The system of claim 19, whercin at least one vessel comprises at least one conduit extending from a bottom of the at least one vessel, the at least one conduit having a length extending to a depth below the bottom.

22. The system of claim 19, wherein the application includes coastal storm protection.

23. The system of claim 19, wherein the application includes storm management.

24. The system of claim 19, wherein the application includes storm deflection.

25. The system of claim 19, wherein the application includes storm reduction.

26. The system of claim 19, wherein the application includes biological population management.

27. The system of claim 19, wherein the application includes biological maintenance.

28. The system of claim 19, wherein the application includes biological enrichment.

29. The system of claim 19, wherein the application includes encouraging coral reef growth.

30. The system of claim 19, wherein the application includes recreational area creation.

31. The system of claim 19, wherein the application includes hurricane reduction.

32. The system of claim 19, wherein the application includes hurricane deflection.

33. The system of claim 19, wherein the application includes hurricane suppression.

34. The system of claim 19, wherein the application includes hurricane prevention.

35. The system of claim 19, wherein the application includes ablation of the floor of the body of water.

36. The system of claim 19, wherein the application includes atmospheric modification.

37. The system of claim 19, whercin thc application includes weather modification.

38. The system of claim 19, wherein the application includes climate modification.

39. The system of claim 19, wherein moving water to lower depths includes moving dissolved or particulate matter in the water to lower depths.

40. A method of environmental alteration, comprising:

determining an application of at least one vessel capable of moving water adjacent the surface of the water to a lower depth in the water primarily using a developed pressure head in the vessel;

placing the at least one vessel in the determined placement; and

generating movement of the water adjacent the surface of the water based on the application.

41. The method of claim 40, wherein the determining an application includes predicting the path of at least one of a tropical depression, a tropical storm, a low pressure atmospheric disturbance, a predicted storm, a hurricane, or a typhoon.

42. The method of claim **40**, wherein the placing the at least one vessel includes adding additional vessels to a group of vessels.

43. The method of claim **40**, wherein the placing the at least one vessel includes moving the vessels by watercraft.

44. The method of claim **40**, wherein the placing the at least one vessel includes moving the vessels by controlling a propulsion device operatively attached to the vessels.

45. The method of claim **40**, wherein the generating movement includes controlling the rate of movement of water.

46. The method of claim **40**, wherein the determining includes placing the at least one vessel over an area in which biological augmentation is desired.

47. The method of claim **40**, wherein the determining includes placing the at least one vessel over an area in which biological destruction is desired.

48.-**49**. (canceled)

50. The method of claim **40**, wherein the placing the at least one vessel includes positioning the vessels to protect beach areas from being damaged by storms.

51. The method of claim **40**, wherein the at least one vessel comprises a tub portion configured to hold water, the tub portion having at least one wall coupled to a bottom portion, the at least one wall extending above the water level and the bottom portion configured to be submerged.

52.-**55**. (canceled)

56. The method of claim **40**, wherein at least one vessel comprises at least one conduit extending from a bottom of the at least one vessel, the at least one conduit having a length extending to a depth below the bottom.

57.-**73**. (canceled)

* * * * *

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Dimov Zhekov

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(54) **HURRICANE PREVENTION SYSTEM AND METHOD**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **11/839,131**

(22) Filed: **Aug. 15, 2007**

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(51) **Int. Cl.**
B63B 35/44 (2006.01)

(52) **U.S. Cl.** 114/264; 210/143

(58) **Field of Classification Search** 114/264, 114/267, 382; 441/1; 405/303; 210/143
See application file for complete search history.

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(57) **ABSTRACT**

The hurricane prevention system and method for use in ocean water is provided including a buoyant platform on which is disposed a wind-driven power source, a water-moving system, and a water-dispersing system. The wind-driven power source is configured to use wind energy to power the water-moving system, which is configured to transport water from somewhat deeper ocean water levels to, or near, the level of the ocean. The water-dispersing system is preferably configured to disperse the water from the water-moving system to an area at or near the sea surface. The buoyant platform preferably is anchored by a mooring system. The hurricane prevention system and method is designed to bring cooler water from deeper in the ocean to or near the ocean surface and to disperse that cooler water in that area to reduce the sea surface temperature, thereby preventing or inhibiting the formation of hurricanes.

17 Claims, 5 Drawing Sheets

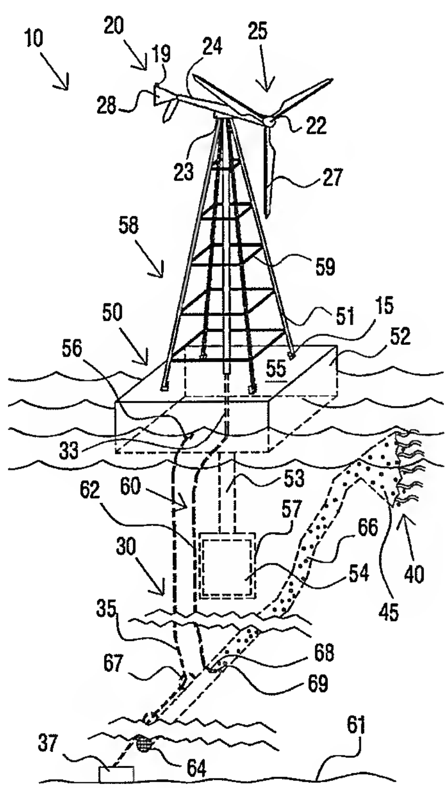

FIG. 1

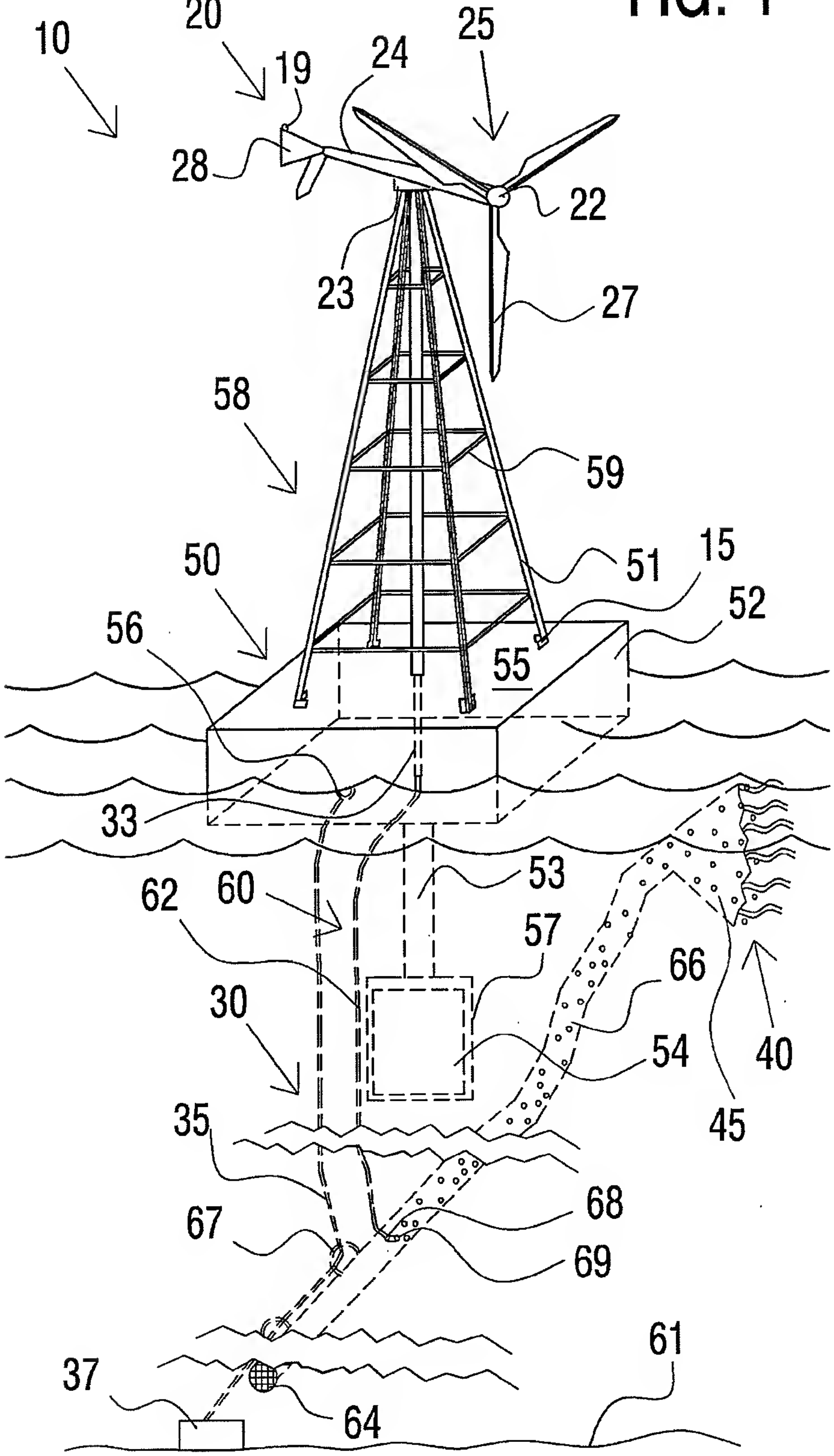
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FIG. 2

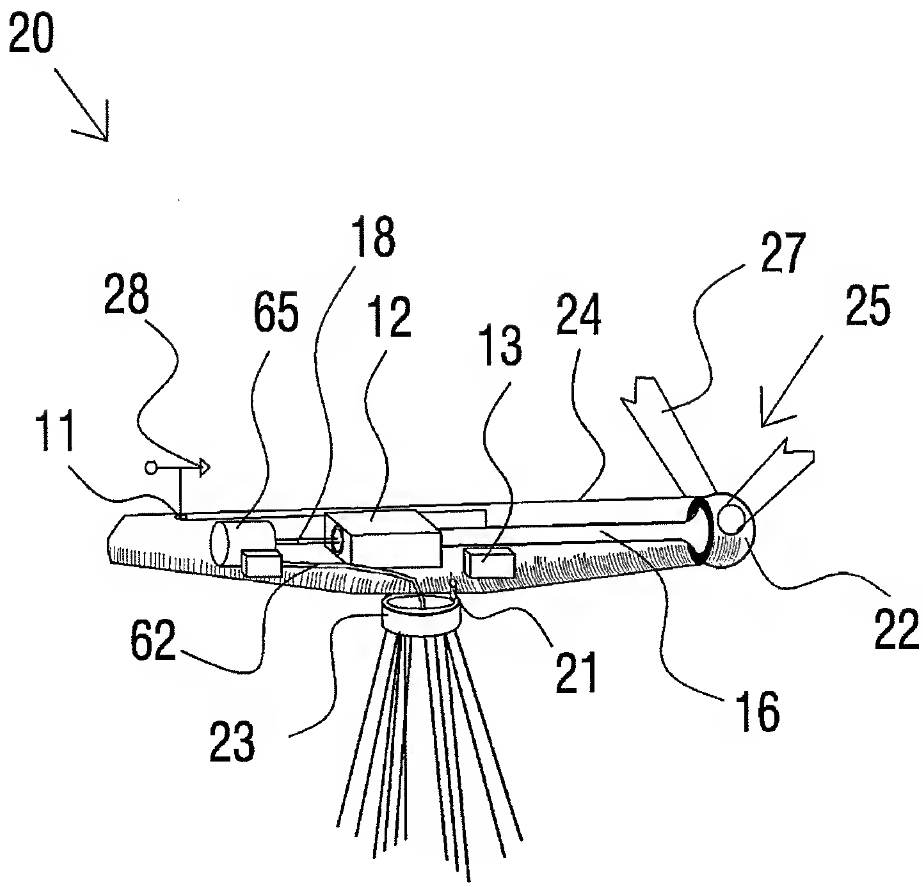


FIG. 3

FIG. 4

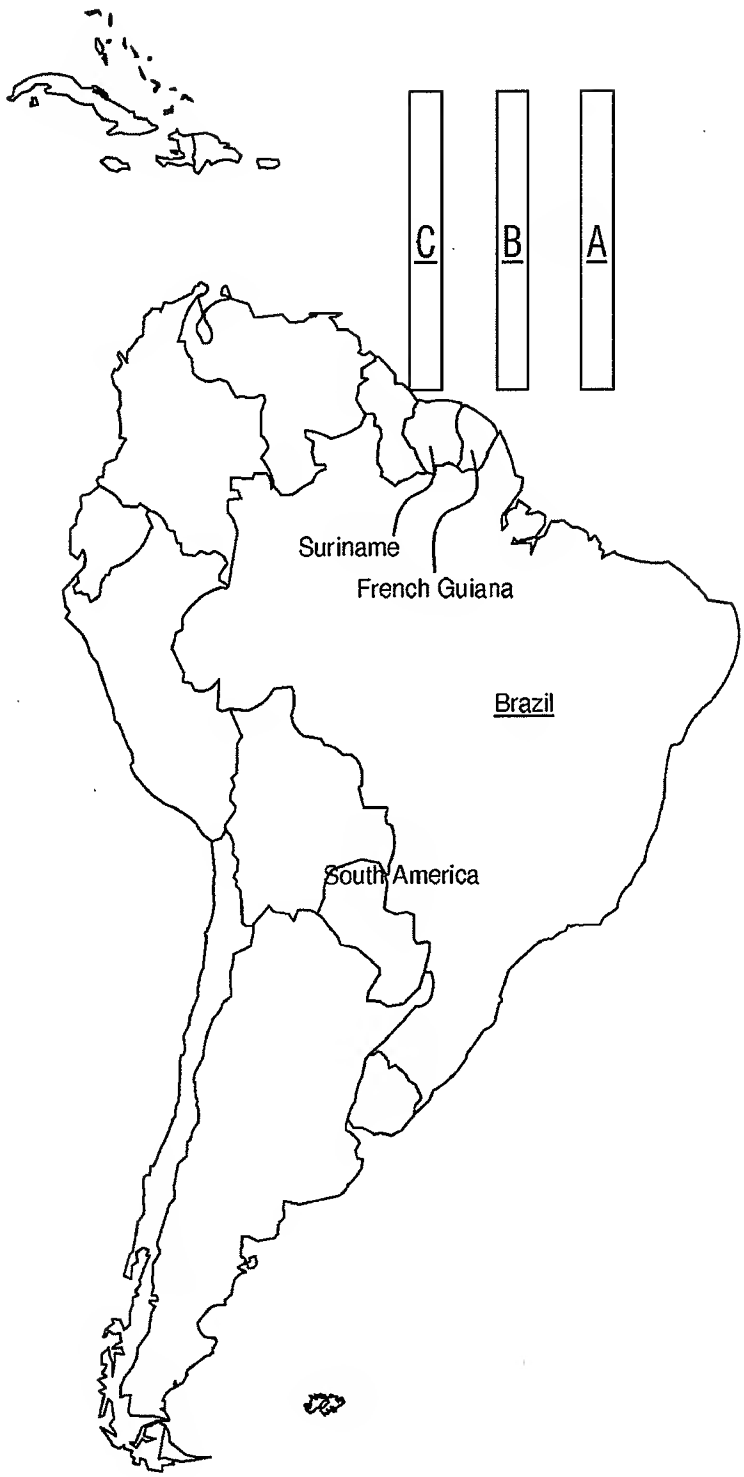
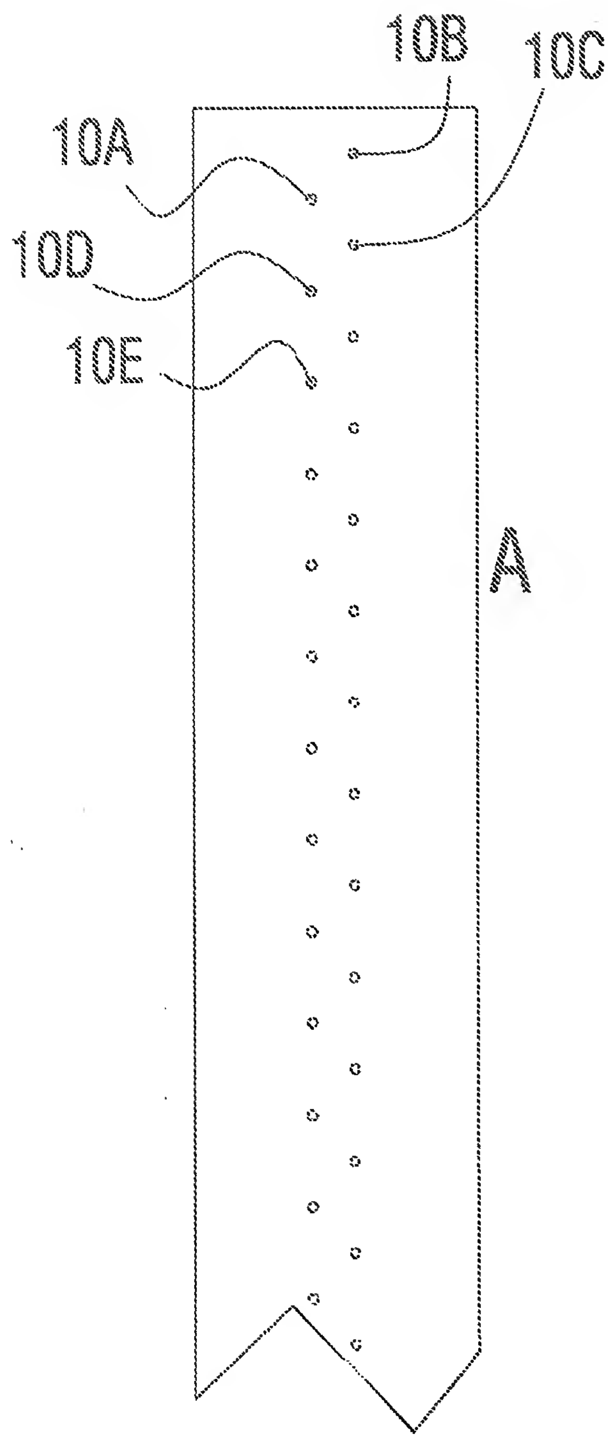


FIG. 5



HURRICANE PREVENTION SYSTEM AND METHOD

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of co-pending U.S. Provisional Patent Application Ser. No. 60/838,078, filed Aug. 16, 2006, which is incorporated herein in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to hurricane suppression or prevention devices and methods, and more particularly, to a hurricane prevention system configured to cool the surface of the ocean water to suppress or prevent hurricanes.

2. Description of the Prior Art

Every year hurricanes extract a huge cost to society in terms of property damage, economic devastation, disruption of businesses and personal life, and, even more, in the number of lives lost. While many attempts have been made to mitigate the damage caused by hurricanes, there is an absence of attempts to actually stop the damage at its source—by attempting to prevent or inhibit the formation of hurricanes.

A study published Mar. 17, 2006 in the journal *Science zdetailed a study of hurricanes since* 1970, which definitively showed that the current rise in the world's sea surface temperatures is the primary contributor to the formation of stronger hurricanes. The new study also reported an alarming trend in the increase in the number of major hurricanes. In the 1970s, the average number of intense Category 4 and 5 hurricanes occurring globally was about 10 per year. Since 1990 the number has nearly doubled, averaging about 18 a year. It is postulated that the trend will continue as sea surface temperatures rise as a side effect of global warming.

It is well known to those in the art that formation of hurricanes requires water temperatures of at least 26.5° C. (80° F.) down to a depth of at least 50 m (150 feet). The huge societal cost of each hurricane coupled with the alarming increase in the number of hurricanes emphasize the importance of providing a system and method to reduce the sea surface temperature to below 26.5° C., thereby preventing or inhibiting the formation of hurricanes.

Accordingly, there is an established need for an effective, feasible hurricane prevention system and method capable of suppressing, inhibiting, or preventing the formation of hurricanes.

SUMMARY OF THE INVENTION

The present invention is directed to a viable, effective hurricane prevention system and method that is capable of bringing cooler water from deeper in the ocean to, or near, the ocean surface and is capable of dispersing the cooler water so that when the cooler water is mixed with the warmer surface water, the sea surface temperature is reduced, thereby preventing or inhibiting the formation of hurricanes. The hurricane prevention system and method includes a buoyant platform on which is disposed a wind-driven power source, a water-moving system, and a water-dispersing system. The wind-driven power source uses wind energy to power the water-moving system, which is configured to transport water from somewhat deeper ocean water levels to, or near, the level of the ocean. The water-dispersing system is preferably configured to disperse the water from the water-moving system to an area at, or near, the sea surface. The buoyant platform preferably is anchored by a mooring system. Preferably numerous buoyant platforms, each with at least one wind-driven power source, at least one water-moving system, and at least one water-dispersing system, are spaced in appropriate locations in the area of the ocean where hurricanes form.

An object of the present invention is to provide a hurricane prevention system and method that can be adapted for use in the areas of the ocean where hurricane formation takes place.

A further object of the present invention is to provide a hurricane prevention system and method that decreases the sea surface temperature.

Another object of the present invention is to provide a hurricane prevention system and method that is configured to reduce the number of hurricanes formed.

An additional object of the present invention is to provide a hurricane prevention system that is configured to use the energy of wind to move cooler deeper water to the sea surface.

These and other objects, features, and advantages of the present invention will become more readily apparent from the attached drawings and from the detailed description of the preferred embodiments, which follow.

BRIEF DESCRIPTION OF THE DRAWINGS

The preferred embodiments of the invention will hereinafter be described in conjunction with the appended drawings, provided to illustrate and not to limit the invention, where like designations denote like elements, and in which:

FIG. 1 is a perspective view showing a first preferred embodiment of the hurricane prevention system of the present invention;

FIG. 2 is a diagrammatic, detail, cut-way view of the nacelle of a second embodiment of the hurricane prevention system of the present invention;

FIG. 3 is a map of North and South American showing an example of a general location of application of the hurricane prevention system of the present invention;

FIG. 4 is a map of South American showing an example of a general location of application of the hurricane prevention system of the present invention; and

FIG. 5 is a diagram of the placement into an array of the individual modules of the hurricane prevention system of the present invention.

Like reference numerals refer to like parts throughout the several views of the drawings.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Shown throughout the figures, the present invention is directed toward a viable, effective hurricane prevention system and method that is capable of bringing cooler water from deeper in the ocean to, or near, the ocean surface and is capable of dispersing the cooler water at the ocean surface. This results in a reduction of the sea surface temperature, and thereby prevents or inhibits the formation of hurricanes (otherwise known as tropical cyclones or typhoons).

Referring now to FIG. **1**, a hurricane prevention system, shown generally as reference number **10**, is illustrated in accordance with a preferred embodiment of the present invention. As shown, the hurricane prevention system **10** includes a wind-driven power source **20**, a water-moving system **60**, a water-dispersing system **40**, a buoyant platform **50**, and a mooring system **30**. Hurricane prevention system **10** is configured for offshore operation in an ocean area where hurricanes form.

The buoyant platform 50 includes an upper base section 52, mid base section 53, and lower base section 57. The buoyant platform 50 is configured such that it has sufficient buoyancy to support the weight of the wind-driven power source 20 and to restrain pitch, roll, and heave motions within acceptable limits, as is known in the art. The technical feasibility of an offshore buoyant platform 50 has been successfully demonstrated by the multitude of buoyant marine and offshore oil platforms that have been utilized for decades.

Upper base section 52 is configured to provide buoyancy to platform 50. Although upper base section 52 is illustrated as substantially square, it may take other shapes as well, such as rectangular, cylindrical, triangular, octagonal, and multi-sectional. The lower surface of upper base section 52 is preferably configured with at least one tether attachment 56.

Mid base section 53 extends below upper base section 52, and serves to connect upper base section 52 to lower base section 57. Lower base sectiou 57, containing a weight ballast 54, is disposed below mid base section 53. Ballast 54 is preferably configured with weight sufficient to keep the buoyant platform 50 upright and with a distribution of the weight that provides added mass moment of inertia to reduce pitch motion of buoyant platform 50. Ballast 54 preferably comprises iron ore ballast, although other ballast suitable for weighting the structure, for example, concrete, iron, lead, magnetite, ballastcrcte, sea water, or the like, can be used. Lower base section 57 can optionally be configured with adjustable ballast compartments utilizing pressure tanks (not shown) that can be partially filled with ballast and partially filled with air, so control over the buoyancy of buoyant platform 50 can be achieved, as is known in the art. Although buoyant platform 50 is illustrated as floating with deck 55 above the level of the water, submerging the platform 50 to minimize the structure exposed to wave loading may prove economically advantageous, and is within the scope of the invention.

The top surface of upper base section 52 is deck 55. A support structure or tower 58 is vertically mounted on deck 55 in a substantially central location. Tower 58 is configured to support the wind-driven power source 20. Tower 58 may be designed as a single upright support structure in a substantially central location (not illustrated) or may comprise structural beams forming upwardly converging legs 51 (as illustrated), secured together as a rigid upright structure with associated bracing 59, as illustrated. The bottoms of legs 51 are spaced apart on the horizontal plane of deck 55, with the tops of legs 51 proceeding upwardly, tapering closer together and intersecting at an apex, pivot connection 23. At vertical intervals, bracing 59 adds rigidity to the beam system. The tower-deck connections 15 between legs 51 of tower 58 and deck 55 are configured to be sufficiently robust to secure wind-driven power source 20 to deck 55 and to support wind-driven power source 20.

Wind-driven power source 20, affixed to and supported by the top of tower 58, is a wind power production system, windmill, or wind turbine, as is known in the art.

Wind-driven power source 20 comprises a nacelle 24, a housing or structure which houses all of the generating components. Nacelle 24 houses a drive train, a propeller 25, a yawing control mechanism, and associated electrical, control, support, and interconnection equipment. Propeller 25 is disposed anteriorly on nacelle 24, and a yawing control mechanism is preferably disposed posteriorly on nacelle 24. Although the hurricane prevention system 10 is illustrated with a horizontal axis wind-driven power source 20, a vertical axis wind-driven power source, as is known in the art, could equally well be used and is within the scope of the invention.

The nacelle 24 is supported by, and rotates on, pivot connection 23 on tower 58.

Propeller 25 comprises a hub 22, partially enclosed and supported by the nacelle 24, and at least one radially extending rigid blade 27 coupled to the hub and adapted to aerodynamically interact with the wind.

Preferably, as is herein illustrated, propeller 25 is comprised of three radiating blades 27 that are spaced at equal angles about a horizontal axis of rotation, generally referred to as a rotor. Blades 27 are individually coupled to a centrally located hub 22, which is connected to nacelle 24. Blades 27, extending in a vertical plane adjacent the side of the tower 58, are relatively long.

Propeller 25 is constantly maintained upwind of tower 58 by a yawing control mechanism supported by nacelle 24 that provides rotation about the vertical axis through pivot connection 23. The yawing control mechanism is illustrated as wind vane 28 in the first embodiment as shown in FIG. 1. For safety, optionally, a navigational warning light 19 is located on wind vane 28 (FIG. 1).

The second embodiment of FIG. 2 is substantially identical to the first embodiment of the hurricane prevention system 10, but illustrates a variation in the yawing control mechanism. The second embodiment includes a second type of yawing control mechanism with a wind-direction sensor 11 at the base of directional vane 29 operatively coupled with a servomotor or computer-controlled motor 13 to turn a yaw control device 21. The computer-controlled motor 13 causes the yaw control device 21 to turn the nacelle 24 so that the propeller 25 faces the wind.

Referring to the diagram of the interior components of nacelle 24 of FIG. 2, the rotor is operatively attached to the main shaft 16 so wind energy is converted into rotational shaft energy. Main shaft 16 operatively attaches to gearbox 12 which outputs energy to power air compressor 65. Gearbox 12 may optionally include other components such as are known in the art for optimum utilization of the available power at the appropriate torques, such as an automatically shiftable power transmission device or clutch (not shown).

The water-moving system 60 of the current invention is designed and configured as an air lift pump, as is known in the art, although other types of pumps could be utilized. The water-moving system 60 preferably comprises air compressor 65 (FIG. 2), an air line 62 (FIG. 1, FIG. 2), aud a water pipe 66 (FIG. 2). Although a variety of differing air lift pumps may be utilized, the anticipated preferred capacity of the air lift pump of the present invention is approximately 3,000 liters/minute for each horsepower of engine utilized.

Air compressor 65, disposed within nacelle 24, is powered by wind-driven power source 20. Air line 62 is supported by tower 58 and is routed downward, preferably along the structure of tower 58, to upper base section 52 (FIG. 1). Uppcr base section 52 provides a conduit 33 through which air line 62 runs, with air line 62 exiting out the lower surface of upper base section 52 and running downward toward the lower, distal end of water pipe 66. Air line 62 fluidly connects air compressor 65 and water pipe 66, providing a pathway for the compressed air from air compressor 65 to travel down to a suitable depth, whereupon air line 62 is attached to discharge water pipe 66 at joint 68.

The compressed air delivered to water pipe 66 lifts an air/water mixture upward through water pipe 66 to the ocean surface or near the ocean surface. The principle generally being that an air/water mixture, with a density lower than the density of water, causes the water to move upward.

Optionally, a foot piece 69 is disposed at joint 68 within water pipe 66 and is configured to break the air into small

bubbles, thereby conserving air and improving efficiency. The foot piece 69 will preferably be disposed at a depth of approximately 8-10 meters. Air line 62 is illustrated as running outside and parallel to water pipe 66, but the lower part of air line 62 can optionally be routed inside discharge water pipe 66 to reduce the likelihood of damage, if desired.

A benefit of the air lift pump is that servicing is simplified due to the fact that there are no moving or wearing components below the sea surface. Optionally, as a substitute for the air lift pump, water moving system 60 can be designed with wind-driven power source 20 charging batteries that can power a water pump on demand, or water can be directly pumped.

The buoyant platform 50 is a vertically moored floating structure configured to be suitable for ocean water depths within the application locations. The buoyant platform 50 is capable of being substantially permanently moored by means of a mooring system 30.

The mooring system 30 includes one or more mooring lines, illustrated as tether 35, whose upper end is secured to the tether attachment 56 of platform 50. It is anticipated that tether 35 will be formed of steel cable, although other suitable materials could be utilized. A single tether 35 may be used, or multiple tethers 35 may be used. For example, four tethers 35 can be used attached to one or more tether attachments 56, preferably located at substantially the four corners of upper basc section 52. Any of the mooring systems as are known in the art may be used, the most common mooring systems being catenary moorings, taut-leg moorings, or vertical tension leg moorings. The choice of mooring type will be dependent not only upon the location, sea depth, and platform design, but also upon economics. The lower end of tether 35 is secured in a manner known in the art to sea floor 61 by anchor 37 (illustrated as a block of concrete). The anchor 37 can be of the available types as are well known, such as gravity-based anchors, drag-embedded anchors, driven pile anchors, suction anchors, driven anchor plates, torpedo embedded anchors, or drilled and grouted pile anchors. Because anchor selection factors—such as bottom soil shear strength, soil weight, and soil material—vary so widely, the anchor will preferably to be specifically designed for the bottom conditions present at the site of application.

Buoyant platform 50 is held in a stable manner by tether 35. Discharge water pipe 66 is preferably routed near tether 35 by means of fasteners 67. The lower end of water pipe 66 is preferably configured with a screen 64 to exclude marine life. The required depth that water pipe 66 is extended is determined by the depth of the water at the site of application of the present invention, but is generally in the area of 450 to 500 feet. At this depth the water temperature is generally around 11 degrees Celsius. The upward end of water pipe 66 is preferably configured with a spout or flat nozzle 45 that is capable of spreading this cooler water from deeper in the ocean. The flat nozzle 45 is preferably disposed at the surface of the water. The spreading of the cooler water increases the mixing of the cooler water with the warmer surface water, thereby lowering the sea surface temperature to below 26.5° C. (80° F.). When the sea surface water is lowered to below 25.5° C., the formation of hurricanes is prevented or inhibited.

Since it is at the approximate temperature of 26.5 degrees Celsius that hurricanes generally begin to form, optionally, the hurricane prevention system 10 can comprise a temperature sensor system with a thermometer for reading the water temperature near the water surface. If the temperature is cooler than approximately 25.5 degrees Celsius a signal is sent to deactivate the air compressor until the water temperature rises again, at which point the temperature sensor system reactivates the air compressor. For example, a clutch may be engaged or disengaged.

The hurricane prevention system 10 may be assembled in place, towed out to location, or placed on a barge to deliver it to location. (not shown) The buoyant platform deck 55 may additionally have communications and/or control equipment located upon it, providing data to study global or climate conditions. (not shown) While hurricane prevention system 10 is illustrated as a single-turbine floating platform 50, a multiple-turbine floating platform could be used, with multiple towers 58 (each supporting a wind-driven power source 20) located on a single larger platform. (not shown)

While the present invention can be utilized anywhere in the world, it is anticipated that the preferable initial use will be in the Atlantic Ocean slightly above the equator, in the general area north of the coasts of the countries of Guyana, Suriname, French Guiana, and Brazil (in the general area of 10° to 16° North and 44° West), in the north trade wind stream area, as shown in FIG. 3. It is in this area that the most dangerous hurricanes that strike the United States are formed. An array of individual modules of the hurricane prevention system 10 can be installed in a single northwardly extending group, illustrated as Array Area A in FIG. 3. Alternatively, multiple arrays of individual modules of the hurricane prevention system 10 can be installed in several groups placed some distance apart, as demonstrated by Array Area A, Array Area B, and Array Area C, in FIG. 4.

A variety of patterns and spacing can be used for the specific placement of the individual modules 10A, 10B, 10C, 10D, etc., of the hurricane prevention system 10 within the hurricane prevention system array. For example, FIG. 5 illustrates an offset pattern allowing an approximate distance of 1500 feet between the individual modules of the hurricane prevention system 10. A single offset row may be used, or, as illustrated, multiple offset rows may be used in the same array area. The specific configuration used will depend upon a variety of location specific factors including, for example, the ocean depth and the usual storm track pattern. The pattern of individual modules within the hurricane prevention system array, as well as the placement of the hurricane prevention system arrays, can be modified as required to meet the goal of reducing the sea surface temperature to below 26.5° C. It should be noted that 1 liter of water with a temperature of 10 degrees Celsius can generally cool 15 liters of water from a temperature of 26 degrees Celsius down to 25 degrees Celsius.

A possible auxiliary positive coutribution of the hurricane prevention system 10 of the present invention, is that bringing the cooler water from deeper in the ocean to the surface additionally may bring water, nutrients, and/or other beneficial components to the surface, allowing for potential improvement of the environment for living organisms in the area of application. While water mass properties are highly asymmetric and site specific, potential may be realized to ameliorate depletion of oxygen in some areas of the ocean.

Since many modifications, variations, and changes in detail can be made to the described preferred embodiments of the invention, it is intended that all matters in the foregoing description and shown in the accompanying drawings be interpreted as illustrative and not in a limiting sense. Thus, the scope of the invention should be determined by the appended claims and their legal equivalents.

I claim:

1. A hurricane prevention system for use in water of the ocean, comprising:

a buoyant platform;

a wind-driven power source disposed on the buoyant platform;

a water-moving system connected to the buoyant platform and powered by the wind-driven power source configured to transport the water from deeper in the ocean toward the surface of the ocean;

a water-dispersing system connected to the buoyant platform and configured to disperse the water from deeper in the ocean;

a mooring system configured to secure the buoyant platform in a generally stable position in relation to an ocean floor; and

a temperature sensor system disposed on the buoyant platform configured to control the activation and deactivation of the hurricane prevention system.

2. The hurricane prevention system for use in water of the ocean as recited in claim **1**, wherein the water-dispersing system comprises a spout.

3. The hurricane prevention system for use in water of the ocean as recited in claim **1**, wherein the water-dispersing system comprises a flat nozzle.

4. The hurricane prevention system for use in water of the ocean as recited in claim **1**, wherein the water-moving system comprises an air lift pump.

5. The hurricane prevention system for use in water of the ocean as recited in claim **4**, wherein the water-moving system comprises an air compressor.

6. The hurricane prevention system for use in water of the ocean as recited in claim **5**, wherein the air lift pump comprises:

a generally vertical discharge water pipe; and

an air pipe fluidly connecting the air compressor to the generally vertical discharge water pipe.

7. The hurricane prevention system for use in water of the ocean as recited in claim **6**, wherein the buoyant platform comprises:

an upper base section configured to provide buoyancy to the buoyant platform, the upper base section comprising an upper surface deck;

a lower base section comprising a ballast; and

a mid-base section disposed below the upper base section and disposed above the lower base section, the mid-base section serving to connect the upper base section to the lower base section.

8. The hurricane prevention system for use in water of the ocean as recited in claim **1**, wherein the wind-driven power source comprises:

a nacelle;

a propeller disposed anteriorly on the nacelle; and

a yawing control mechanism disposed posteriorly on the nacelle.

9. The hurricane prevention system for use in water of the ocean as recited in claim **8**, further comprising a tower to support the wind-driven power source and to secure the wind-driven power source to a deck of the buoyant platform.

10. The hurricane prevention system for use in water of the ocean as recited in claim **9**, wherein the buoyant platform comprises:

an upper base section having at least one tether attachment and having an upper deck surface, wherein the tower is disposed on the upper deck surface;

a lower base section comprising a ballast;

a mid-base section disposed below the upper base section and disposed above the lower base section, the mid-base section serving to connect the upper base section to the lower base section;

at least one anchor; and

at least one tether secured at its upward end to the at least one tether attachment of the upper base section of the buoyant platform and secured at its lower end to the at least one anchor.

11. The hurricane prevention system for use in water of the ocean as recited in claim **10**, wherein the yawing control mechanism comprises a wind vane.

12. The hurricane prevention system for use in water of the ocean as recited in claim **11**, wherein the at least one anchor is comprised of concrete.

13. The hurricane prevention system for use in water of the ocean as recited in claim **11**, wherein the at least one tether is comprised of steel cable.

14. A method to inhibit the formation of hurricanes, comprising:

generating power via a wind-driven power source disposed on a buoyant platform;

powering a water-moving system with the power;

transporting water from deeper in an oceau toward a surface of the ocean via the water-moving system;

dispensing the water from deeper in the ocean near the surface of the ocean;

spreading the water from deeper in the ocean in a manner to cause the mixing of cooler water of the ocean surface with the water from deeper in the ocean;

sensing a temperature of the water near the surface of the ocean;

deactivating the water-moving system if the sensed temperature of the water near the surface of the ocean is cooler than approximately 25.5 degrees Celsius; and

reactivating the water-moving system if the sensed temperature of the water nears the surface of the oceau is warmer than approximately 25.5 degrees Celsius.

15. The method to inhibit the formation of hurricanes as recited in claim **14**, wherein the wind-driven power source is a wind turbine.

16. The method to inhibit the formation of hurricanes as recited in claim **15**, wherein the water-moving system utilizes a generally vertical discharge water pipe to transport the water from deeper in the ocean to the ocean surface.

17. The method to inhibit the formation of hurricanes as recited in claim **16**, further comprising:

transporting compressed air from an air compressor powered by the wind-driven power source to a lower area of the generally vertical discharge water pipe; and

mixing the compressed air from the air compressor with the water in the generally vertical discharge water pipe, whereby the water in the generally vertical discharge water pipe is encouraged to rise toward the surface of the ocean.

* * * * *

Atmocean, Inc.™

Atmocean, Inc | Pump Technology | Business | Applications

Atmocean's wave-driven ocean upwelling system operates in the open ocean hundreds of miles from land where there is a steady supply of large ocean waves. Each pump, typically reaching down to depths of 100 meters to 400 meters beneath the surface, employs a surface buoy to capture this kinetic wave energy and pump the deep ocean toward the surface.

The deeper ocean is both colder and contains higher levels of nutrients. Upwelling of this deeper ocean, whether caused by storms and currents or by future deployment of Atmocean pumps, triggers the growth of phytoplankton. To metabolize the nutrients, phytoplankton take in dissolved CO_2. This natural process today is absorbing nearly half of mankind's emissions of CO_2 while providing food for nearly all life in the upper ocean. But global warming is stratifying the upper ocean and reducing nutrients which reach the sunlit zone. Fewer phytoplankton grow, diminishing the ocean food chain and absorbing less CO_2. This causes a feedback loop as more warming lessens natural ocean absorption of CO_2, which then remains in the atmosphere to cause more warming.

In the years and decades ahead, Atmocean believes our wave-driven ocean upwelling system – which closely mimics and slightly enhances the natural ocean process - can play a critical role in restoring our ocean environment and cutting short this feedback loop. On the adjoining pages you can learn more about how our technology works and some of its applications. For more details, please contact Philip W. Kithil, CEO, at atmocean.kithil@gmail.com

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Atmocean is developing its proprietary wave-driven ocean upwelling system to cool the upper ocean and enhance natural biological processes to absorb CO_2. When widely deployed across critical ocean regions, the Atmocean technology can help fight global warming by sequestering massive amounts of CO_2 on the ocean floor, reduce hurricane intensity, and help revive ocean fisheries.

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Downsizing Hurricanes Using Atmocean's Upwelling System

While climate scientists differ if hurricanes are more intense from global warming, all agree the damages caused by the 2005 Gulf of Mexico hurricanes could portend tremendous damages and loss of life from future large storms.

Is any technology able to downsize these powerful storms? Given that hurricane tracking forecasts are accurate only a few days ahead, could the technology be correctly positioned soon enough? Would the storm veer off, hitting a different region?

Hurricane intensity is strongly linked to upper ocean heat content. Mathematical models show Atmocean's upwelling system pre-cools the upper ocean by a few degrees C., reducing the evaporative energy to the hurricane, and lowering winds up to 15%. Since hurricane damages are proportional to the cube of windspeed, losses could be reduced up to 40%. By relying on wave kinetic energy, the system naturally self-calibrates due to the much larger waves generated by a storm.

Atmocean's upwelling arrays would be positioned beginning at 200 meters depth along the Gulf and East coast, and extend seaward in a band about 150 km wide, as seen above.

If Atmocean arrays had been in position ten years ago, our storm track analysis shows they could have intercepted and quite likely reduced the intensity of 84% of US-landfalling hurricanes.

HURRICANE SUPPRESSION BY SEA SURFACE COOLING

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ABSTRACT

Hurricane intensification can be prevented by cooling critical areas of the sea surface. Deep cold water can be pumped up and distributed at the surface through long perforated fabric hoses. Water overlying the Gulf Coast continental shelf from Texas to the Florida Keys can be cooled by water pumped from 200-meter depth using electric power transmitted by sub-sea cables from the shore grid. Portions of the Gulf of Mexico's Loop Current and its warm-core eddies might be cooled by moored pumping stations powered by Ocean Thermal Energy Conversion (OTEC).

1. INTRODUCTION

This paper is a study of the possibility of preventing or mitigating hurricanes by reducing the sea-surface temperature (SST) in hurricane-prone areas. The critical SST necessary for hurricane formation and growth is in the range 27 – 29 °C. [1] Whether a hurricane actually forms and the intensity it attains depends on a number of factors. However, the thermodynamic limit to its intensity can be predicted from the SST and the vertical temperature structure of the atmosphere. [2] The intensity of a hurricane can be represented by its minimum central pressure. In a sampling of 56 observed Atlantic hurricanes, 8 reached or came close to the central pressure predicted by a theory in which SST was a major factor. [2] Therefore, it is reasonable to conclude that reduction of SST should be a way to eliminate or mitigate hurricanes.

We are particularly interested in reducing SST in the Gulf of Mexico (GOM) because of its vulnerability and demonstrated potential for damage, human suffering, and economic loss. The method proposed for cooling the surface is to pump cold water up from the bottom and spread it thinly and evenly at the surface so that it will not sink before it mixes with the surface water.

Water flows into the GOM via the Yucatan Channel, which is 150 km wide at a depth of 800 m. The sill is 50 km wide and is 1900 m deep. [3] There is a strong diurnal (approximately 24 hr period) tidal flow superimposed on a steady flow of about 25 Sv (25 x 10^6 m^3 s^{-1}). [4] Two almost-equal diurnal tidal components beat with each other. The fortnightly peaks of their beat pattern add 30 Sv to the 25 Sv steady flow, giving peak flows into the GOM of 55 Sv. Twelve hours later, the tidal flow opposes the steady flow, resulting in a backward flow of as much as 10 Sv when other tidal flow components are included. Semi-diurnal tidal components have weak flows in the Yucatan Channel but these tides are amplified at the west and east ends of the Gulf. Therefore all tidal components affect the shelf region from Texas to the Florida Keys.

The tidal motion tends to spread cooling water over the surface but it also tends to sweep it away. This is a complicated problem and I presently have no quantitative estimate for the influence of tidal and other currents on the rate at which cold water must be supplied to lower the SST. One indication that this influence may not be too great is the fact that during 21 – 27 August 2005 the SST on the shelf was greater than 30 °C while the SST of the rest of the Gulf was below 30 °C. [5] This suggests that local cooling of the shelf is desirable and may well be possible.

2. LOCAL COOLING OF THE SEA SURFACE OVER THE GULF COAST CONTINENTAL SHELF

Consider a vertical pipe at the 200 m isobath (constant depth contour) where the bottom temperature is 13.5 °C. Water flowing at 3 m s^{-1} in a pipe whose inside diameter is 5 m delivers 58.9 m^3 s^{-1} to the surface, where it is distributed by pumping it into a long perforated fabric hose. The hose diameter is 5 m and it is kept at the surface by floats, if necessary. The hose is inflated by pump pressure, and the diameter might taper down toward the end in order to maintain sufficient pump pressure to keep it inflated. The shore might be as much as 200 km away and the hose might be 1 km long, so the hose can point in any direction, as far as cold water distribution is concerned. It might be allowed to pivot freely to follow the current, or be constrained by moorings. If we mix the cold water into surface water whose temperature is 27 °C, the 13.5 °C water will experience a temperature rise of 13.5 °C. The cold water has a density of 1026.9 kg m^{-3} before mixing, so the heat transfer rate is

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13.5(1026.9)58.9(4186) = 3.42 GW, where 4186 is the number of Joules per kilocalorie.

The average density of a 200 m column of water outside the pipe is 1025.73 kg m^{-3}. The difference in density (1026.9 – 1025.73) kg m^{-3} requires a pressure (or suction) of 2296 Pa to raise the water in the pipe. Pipe friction in the 200-m vertical pipe and the 1000-m perforated distribution hose is estimated to require an additional pressure of 29.39 kPa. The total pressure of 31.69 kPa multiplied by the flow of 58.9 m^3 s^{-1} and divided by the pump efficiency of 76% gives an electrical power requirement of 2.46 MW per pump.

The water surface loses heat by evaporation, convection to the atmosphere, and long-wave radiation to space or cloud cover. Reducing SST will decrease the evaporation and convection loss, imposing a positive load on our cooling system. Reducing SST increases the radiation loss because the relative humidity directly over the water is reduced, and this reduces the load on our cooling system.

For this calculation, assume that a 27 °C SST is reduced to 25 °C. Equation (5.3) of [6], not repeated here, gives an approximation for evaporation loss in terms of saturated vapor pressure over the sea surface, vapor pressure at 10-m altitude, wind speed, and latent heat of evaporation at the SST. A wind speed of 4 m s^{-1} was assumed. During the change of SST from 27 to 25 °C, it is assumed that the vapor pressure at 10 m altitude does not change, so the decrease in evaporation rate depends only on the change in water vapor pressure just above the surface. For the 2 °C drop in SST, the evaporation heat loss decreases by 6.01 W m^{-2}.

Bowen's Ratio is the ratio of convection loss to evaporation loss and, according to p. 82 of [6], is approximately 0.1 for equatorial and tropical regions. Therefore the convection loss decreases 0.6 W m^{-2}, and it also adds to the cooling load.

Fig. 5.6 and Equation (5.2) of [6] give the long-wave infrared radiation loss from the sea surface. A relative humidity of 80% and heavy cloud cover were assumed. The 2 °C decrease in SST increases the radiation loss by 0.35 W m^{-2}, which is a negative cooling load.

The 2 °C decrease in SST causes a cooling load of 6.01 + 0.6 – 0.35 = 6.26 W m^{-2}. The shelf area to be cooled is estimated to be 3.89 x 10^{11} m^2, so the cooling load is 6.26 (3.89 x 10^{11}) = 2435 GW. The cooling rate of a single pump is 3.42 GW when the 13.5 °C water is mixed with 27 °C water. When we achieve the desired reduction in SST, the cold water will experience a temperature rise of 11.5 instead of 13.5 °C, so we should use the average temperature rise of 12.5 °C to calculate the single-pump cooling rate. (12.5 / 13.5) 3.42 = 3.17 GW. We will need 2435 / 3.17 = 768 pumps to handle the evaporation, convection, and radiation load.

The 200-m isobath was chosen arbitrarily for the pump location. Moving at least some of the pumps to deeper, colder water would achieve greater cooling with very little increase in required pumping power.This possibility will be investigated. Continuing with the present choice, the 768 pumps will move 768 (58.9) = 4.52 x 10^4 m^3 s^{-1}, which is 0.18% of the average flow through the Gulf and the Florida Straits. The pumps will consume 768 (2.46 MW) = 1.89 GW, which is slightly greater than one third of the LIPA (Long Island, New York) peak summer demand. This power can be supplied by sub-sea cables from several points in the Gulf Coast electric power grid. If the pumps can be placed on the sea floor, the water can be pushed up in a flexible fabric hose. This requires that the motor and speed reducer be housed in a waterproof case with a pump shaft seal that can withstand the hydrostatic pressure at 200-meter depth. The availability of such seals is not yet known to the author.

If the pump must be at shallow depth, the suction pipe might be made of 10-m-long flanged sections of fiberglass-reinforced plastic pipe. The sections would be coupled together by a grooved band strapped around the flanges. The pump housing would have excess buoyancy so that moorings would always be taut in order to restrain vertical motion due to waves and tides. Without this restraint, the inertia of the water in the pipe would resist following the upward acceleration of the pump and suction pipe. The pressure in the top of the pipe would drop below the vapor pressure of the water, and boiling would allow the water column to drop and interrupt pump operation.

At this time we do not have an easy, simplistic estimate for the number of additional pumps required to replace the cooling water that is swept away by the currents. It is possible that this missing estimate can only be obtained from a detailed study of actual currents, or a fine-resolution computer model. Funding must be provided in order to obtain these services.

However, in a never-ending search for easy, simplistic answers, one might ask why the water above the northern and eastern shelves was above 30 °C while the rest of the Gulf had a SST below this temperature. One might guess that the solar heated shallow water over the continental shelves was not able to lose heat at night by convection because there was limited access to deeper, colder water. The higher SST that was allowed to remain over the continental shelf may indicate that the current system may have a limited ability to sweep away cold water that is pumped up to cool the surface. So perhaps we will not require many more pumps than the 768 already estimated.

It may be comforting to note that whatever cooling water is swept away from the shelf passes through the

Florida Straits and enters the North Atlantic Ocean as the Florida Current. This feeds the Gulf Stream which carries the cooled water (much diluted by now) into the North Atlantic Subtropical Gyre. Some of this water diverts into the North Atlantic Current and eventually reaches the Arctic. So in a very small way, the pumping of cold water in the GOM helps to retard Arctic ice sheet melting and thereby slows sea level rise.

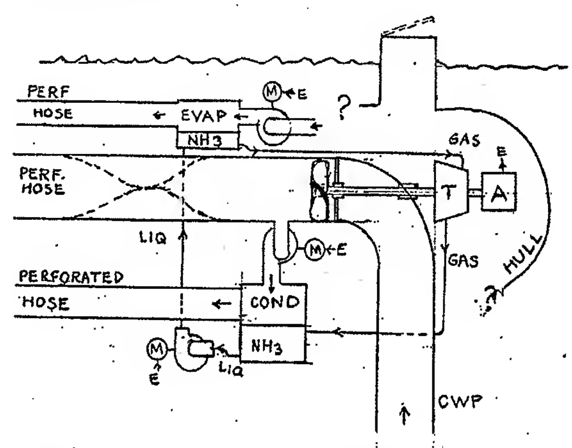
3. PUMPS POWERED BY OCEAN THERMAL ENERGY CONVERSION (OTEC)

The Loop Current that flows between the Yucatan Channel and the Florida Straits is very unstable. There are times when the current emerges from the Yucatan Channel traveling toward New Orleans, makes a clockwise U-turn and then makes a left turn into the Florida Straits. The clockwise U-turn elongates into a loop which penetrates into the Gulf. Eventually, the loop pinches together to form a closed ring that detaches from the main loop current. The ring, also called an eddy, then drifts slowly toward the west.

The clockwise circulation around the ring, and the clockwise turning of the loop cause warm water to be swept toward the respective centers of the ring and the loop. This results from the Coriolis force, which is directed perpendicular to the direction of the current. The warm water in a ring can extend down 150 meters from the surface [7] instead of conforming to the temperature gradient normally found in the Gulf. [8] Clockwise rings in the Northern Hemisphere are called warm-core rings. Hurricane Katrina passed over the loop and an almost-detached ring as it headed toward New Orleans. These patches of deep warm water can supply a tremendous amount of latent heat to energize a passing hurricane.

The deep central area of the Gulf, where these warm-core eddies detach, has 5 °C water available at 1000 m depth. [8] Pumping power can be derived from a heat engine that uses the warm water at the surface as a heat source and the cold water pumped up through a long pipe as the heat sink. There is only a 22 °C difference between the source and sink so the theoretical maximum (Carnot) efficiency is $(27 - 5) / (27 + 273) = 7.3$ %. This means that the mechanical power that the engine can produce is limited to 7.3 % of the rate at which heat energy is passed from the source to the sink. The source and sink are water, but the working fluid in the heat engine would probably be ammonia. Heat exchangers must be used to transfer heat to and from the ammonia. Temperature drops in the heat exchangers and other practical considerations make the actual operating efficiency much less than 7.3 %.

Solar energy absorbed by and stored in the upper layer of the ocean is the energy source for the heat engine. The process of converting this heat energy into mechanical energy is called Ocean Thermal Energy Conversion (OTEC). In the present application, the cold water is pumped up through a cold-water pipe 1000 m long and into a condenser heat exchanger in which ammonia vapor is condensed after it exits from a turbine (T). The liquid ammonia is pumped to a higher pressure and enters the evaporator. Warm surface water is pumped through the water passages of the evaporator heat exchanger and the ammonia is vaporized. The ammonia vapor exits the evaporator and enters the turbine where it expands through rotor blades that turn the shaft. The spent vapor exits the turbine at a lower pressure than that at the turbine inlet, and goes to the condenser, completing the thermodynamic cycle.



The turbine shaft is connected through a speed reducer to the large-diameter axial-flow rotor of the main pump. The turbine shaft also drives an alternator (A) which is used to power several pumps. One pump takes warm water from upstream at the rate of 27.8 $m^3 s^{-1}$ and pushes it through the evaporator heat exchanger. From there it is carried downstream by a long perforated fabric hose. Another pump takes the liquid ammonia from the condenser and raises its pressure to that of the evaporator so that it can enter the evaporator to be vaporized to power the turbine. The third electrically-powered pump takes cold water from the output port of the main pump and supplies the extra pressure required to push water through the passages of the condenser heat exchanger. The water discharged from the condenser is sent downstream in another perforated fabric hose so that it can mix with the surface water. The electric motors driving these three pumps are labeled (M), and (E) represents the electric power supplied to them by the alternator.

The main pump is axial flow and large diameter because it pumps a large volume of water with a low pressure differential. Its rotor, a multi-blade fan, is located

in the horizontal output leg of a right-angle elbow. The vertical input leg of the elbow faces down and connects to the 1000-m-long cold-water pipe. The pump rotor shaft comes through the elbow wall and connects to the output shaft of the turbine's gear box. The inside diameter of the cold-water pipe, the elbow, and the pump section is 5 m. The velocity is 3 m s^{-1} and the flow is 58.9 m^3 s^{-1}. The condenser diverts 14.6 m^3 s^{-1} from the output of the main pump and the remaining 44.3 m^3 s^{-1} enters a third perforated fabric hose that extends downstream. The use of separate discharge hoses for the three pumps avoids the problem of balancing their output pressures.

The OTEC plant will not self-start. An auxiliary boat must supply electrical power to the evaporator, condenser, and ammonia pumps. The fabric hose on the output port of the main pump collapses, as shown by the dotted lines in the sketch, to act as a check valve. This insures that the condenser pump draws cold water up from the bottom, rather than warm water from the surface. An electronic inverter will synchronize the auxiliary supply with the phase of the turbine-driven alternator when it is up to speed. Then the pump motors can be switched to the alternator and the pumping station will be powered by its OTEC plant.

The performance of this design is scaled from a proposal by Vega [9] for a slightly smaller OTEC plant that uses 26 °C top water and 4.5 °C bottom water to produce a net electrical output of 5.26 MW. In the case of the present pumping station, the net output is not electrical power. It is the work done by the main pump and some extra power used by the evaporator and condenser pumps to overcome the back pressure of their respective perforated discharge hoses, which were not used in the Vega design. The OTEC plant supplies the power for its pumps (except as noted above) and this is not included in the net output. The difference between warm and cold temperatures in the present design is almost the same as in the Vega design, so the efficiencies should be the same.

The pumping station configuration described here is intended to be used in a well-defined surface current. The warm water intake must face upstream and the perforated discharge hoses must trail downstream so that the warmest water is used in the evaporator. Operation of such a plant in the area where the loop and rings are developing and separating presents the problem that the pumping station will be operating in a current that might be changing direction. It might be necessary to design a mooring that allows the station to swing around to follow the current direction. The vertical cold-water pipe should be at the center of rotation with a circular track on a fixed mooring platform. The pumping station could be rotated around the track by a motor controlled from satellite observations of the current direction. This varies slowly over a period of months.

The mooring must be anchored to the bottom by cables that are kept taut because the pumping station has excess buoyancy and is pulled into a submerged position. The submerged operation insures that there is positive pressure at all pump inlets to prevent cavitation, but the primary reason is to maintain the tautness of the mooring cables so that the pumping station does not accelerate up and down in large waves. Downward acceleration of the station and its cold-water pipe would cause large pressure surges that would damage the pumps and other components. Upward acceleration would reduce the pressure in the top of the pipe below the vapor pressure of water. This would result in boiling and separation of the water column with resultant starvation of the pumps and probably interruption of the OTEC operation. The taut-cable submerged mooring just described is similar to the tension-leg platforms used in the deepwater offshore oil and gas industry.

OTEC has had a long development history, adequately described in [10] and other literature. OTEC plant ships on the high seas have been suggested as a means to produce ammonia and other products that could be periodically transported to shore. Adequate attention has been given to the use of a universal joint between the cold-water pipe and the platform to accommodate rocking and pitching motion. However, there seems to be no mention of possible up-and-down motion. Comments on this and other questions and statements would be appreciated.

An attempt has been made to estimate the number of pumping stations required to cool a detached ring, assuming that they are all located in the warm central core. This is a somewhat optimistic premise if the ring is detached and drifting, but we need some estimate that indicates whether the idea is feasible. The warm core that Katrina passed over is estimated to have a diameter of about 2 degrees of latitude, which is 223 km. [11, 12]. If it has a uniform temperature down to 150 m, its volume is 5.84×10^{12} m^3. This core had a temperature of 30 °C, so an OTEC plant operating here would have better performance than predicted for the 27 °C SST, but this will not be taken into account. Scaling from the Vega design, the main pump discharges 44.3 m^3 s^{-1} at 5 °C which, when mixed with 30 °C water gives a cooling rate of 44.3 (30 − 5) = 1107 m^3 °C s^{-1}. The condenser discharges 14.6 m^3 s^{-1} at 10.8 °C, giving a cooling rate of 14.6 (30 − 10.8) = 281 m^3 °C s^{-1}. The evaporator discharges 27.8 m^3 s^{-1} at 26.9 °C, giving a cooling rate of 27.8 (30 − 26.9) = 86 m^3 °C s^{-1}. The sum of these cooling rates is 1474 m^3 °C s^{-1}, which will cool the core at the rate $1474 / 5.84 \times 10^{12} = 2.53 \times 10^{-10}$ °C s^{-1} or 6.55×10^{-4} °C per month. To cool the core at the rate of 1 °C per month requires $(6.55 \times 10^{-4})^{-1} = 1528$ stations. Formation and detachment of a ring is a slow process and perhaps this

cooling rate would be useful, especially if it is done continuously throughout the year.

It will take much further study to determine whether permanent or long-term mooring locations of the pumping stations can insure that most of them will be located at hot spots of SST. This is where the stations must be placed so that warm water will keep rising up to the station. The Coriolis force acting on the geostrophic current of the ring, moves the warm water toward the center of the ring. A cooling station is most effective if it receives a steady replacement of warm water. There is much less benefit from cooling already-cool water.

One might be tempted to place cooling in the path of a current such as the loop current. A study that preceded this study found that it would require about 20,000 of these stations to keep the main stream through the GOM 3 °C below the maximum upstream temperature. The estimate for warm-core cooling demonstrates that it is easier to cool an area whose heat is not being replenished by the main stream.

4. CONCLUSION

It may be possible to prevent or mitigate hurricanes by cooling the sea surface of the Gulf of Mexico at specific locations, such as the continental shelf of the Gulf Coast and the warm-core eddies that detach from the Loop Current. Pumps on the shelf can be powered by sub-sea cables from points on the shore grid. Pumping stations moored in the eddies can be powered by ocean thermal energy conversion (OTEC). The rate at which cold bottom water must be pumped up and mixed with the surface water makes this solution neither easy nor cheap. But it may be the only one that works. The politically-correct exhortation to reduce greenhouse gas emissions is constructive, but it can only decrease the *rate* at which greenhouse gas atmospheric concentrations are *increased.*

The author believes that sea surface cooling merits consideration by the oceanographic, marine, environmental, maritime, offshore, and many other sciences and industries, as well as politicians, the public, insurance companies, financial institutions, and others. This paper has concentrated on the technical feasibility of providing enough sea-surface cooling to actually improve the hurricane statistics. The environmental consequences, good and bad, of upwelling large quantities of water, and the legal, financial, and many other questions must be examined. It is obvious that many people with various talents must be involved in order to make this idea work.

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6. AUTHOR'S BIOGRAPHY

Richard LaRosa earned BEE, MEE, and DEE degrees from the Polytechnic Institute of Brooklyn. During his engineering career in microwaves and electronics he experimented with solar energy and taught courses in solar thermal engineering. He wrote and edited many articles on energy conservation and renewable energy. Reporting on these technologies made him realize that they would always be practiced on too small a scale to solve the global problems of climate change, sea level rise, and fresh water shortages. A detailed study of the greenhouse effect came next, followed by the realization that ocean currents like the Gulf Stream could be slowed by extracting energy from them. Then came the understanding that this would be a very bad thing to do, which brings us to sea-surface cooling.

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Atmospheric Chemistry and Physics

Simulation of hurricane response to suppression of warm rain by sub-micron aerosols

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Abstract. The feasibility of hurricane modification was investigated for hurricane Katrina using the Weather Research and Forecasting Model (WRF). The possible impact of seeding of clouds with submicron cloud condensation nuclei (CCN) on hurricane structure and intensity as measured by nearly halving of the area covered by hurricane force winds was simulated by "turning–off" warm rain formation in the clouds at Katrina's periphery (where wind speeds were less than $22\,\mathrm{m\,s^{-1}}$). This simplification of the simulation of aerosol effects is aimed at evaluating the largest possible response. This resulted in the weakening of the hurricane surface winds compared to the "non-seeded" simulated storm during the first 24 h within the entire tropical cyclone (TC) area compared to a control simulation without warm rain suppression. Later, the seeding-induced evaporative cooling at the TC periphery led to a shrinking of the eye and hence to some increase in the wind within the small central area of the TC. Yet, the overall strength of the hurricane, as defined by the area covered by hurricane force winds, decreased in response to the suppressed warm rain at the periphery, as measured by a 25% reduction in the radius of hurricane force winds. In a simulation with warm rain suppression throughout the hurricane, the radius of the hurricane force winds was reduced by more than 42%, and although the diameter of the eye shrunk even further the maximum winds weakened. This shows that the main mechanism by which suppressing warm rain weakens the TC is the low level evaporative cooling of the un-precipitated cloud drops and the added cooling due to melting of precipitation that falls from above.

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1 Introduction

The devastating United States hurricane season of 2005 renewed interest in developing methods to mitigate the strong winds of hurricanes. Hurricane modification can be considered if it is possible to intervene in the energy pathways in moist tropical convective clouds that energize hurricanes. These energy pathways (see illustration in Fig. 1) start with heat that is taken from the sea surface mainly by evaporation (Fig. 1A). This latent heat becomes sensible when the vapor condenses into cloud drops (Fig. 1B). Some of this released heat is reclaimed if the drops re-evaporate (Fig. 1C), but the heat remains in the air if the drops precipitate as rain (Fig. 1D). Drops that ascend to the sub-zero parts of the cloud freeze and release additional latent heat of freezing (Fig. 1E), which along with the freezing of the ascending vapor warm the upper levels of the cloud (Fig. 1G). Some of the heat is lost when ice evaporates aloft (Fig. 1I). The rest of the heat remains in the cloud when the ice hydrometeors precipitate and melt while cooling the air below (Fig. 1H). This study tests the feasibility of modifying hurricanes by seeding with small CCN to suppress warm rain (Fig. 1D). This would increase the warming aloft (Figs. 1E and G) and the evaporative cooling at the lower levels (Figs. 1C and H) and so affect the storm circulation in ways that will be shown herein.

Historically the pathway of freezing supercooled cloud water (Fig. 1E) was addressed by glaciogenic cloud seeding. Hurricane mitigation was first attempted between 1962 and 1983 in the framework of project STORMFURY by the US government (Willoughby et al., 1985). The envisioned modification technique involved artificial stimulation of convection at the outer periphery of the eyewall through seeding of strong convective cloud towers with silver iodide for the purpose of freezing super-cooled water (water in liquid state but colder than 0°C). They postulated that the release of the latent heat of freezing (pathway E in Fig. 1) would invigorate convection (Simpson and Malkus, 1964) that would

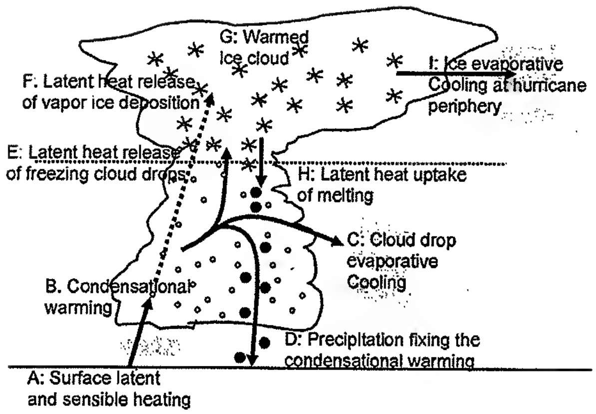

Fig. 1. Energy pathways in the convective clouds that energize hurricanes. The heat that is taken from the sea surface mainly by evaporation (A) is released when the vapor condenses into cloud drops (B). Some of this released heat is reclaimed if the drops re-evaporate (C) and return to vapor. The heat remains in the air if the drops precipitate as rain (D). Drops that ascend to the sub-zero parts of the cloud freeze there and release additional latent heat of freezing (E), which along with the freezing of ascending vapor warm the upper levels of the cloud (G). Some of the heat is lost when ice evaporates aloft (I). The rest of the heat remains in the cloud when the ice hydrometeors precipitate and melt while cooling the air below (H). Seeding by small CCN to suppress warm rain (D) would increase the warming aloft (E and G) and evaporative cooling at the lower levels (C and H).

compete with the original eyewall, leading to its reformation at a larger radius, and thus, through partial conservation of angular momentum, produce a decrease in the strongest winds. Since a hurricane's destructive potential increases with the cube of its strongest winds, a reduction as small as 10% in its wind speed could significantly reduce the destructive power of hurricanes, which is proportional to the cube of the wind speed.

Modification was attempted in four hurricanes. Although the maximum winds of some of the seeded TCs decreased, the change in hurricane intensity was attributed to natural intensity fluctuations rather than to seeding. The analysis of the microphysical structure of tropical convective (TC) clouds (Willoughby et al., 1985) showed that at the levels where seeding was applied there was too little supercooled water and a significant amount of cloud ice. Consequently, the glaciogenic seeding was not likely to affect cloud dynamics, at least in the way assumed in the STORMFURY conceptual model. Today it is known that the quick conversion of cloud water into raindrops (Pathway B in Fig. 1) in maritime tropical convection causes the clouds to lose much of their water by rain out and evaporation (Pathway C) before ascending above the 0°C isotherm.

This study was motivated initially by earlier observations that a heavy load of small aerosols can prevent warm rain from tropical clouds (Rosenfeld, 1999; Rosenfeld and Woodley, 2003; Andreae et al., 2004), and hence allow the cloud water to ascend to the supercooled levels and become available for freezing, and so remedy the cardinal problem of STORMFURY, which is insufficient amounts of supercooled water. The low amounts of supercooled water are caused by the very efficient warm rain processes and early rainout in tropical maritime convective clouds (Jorgensen and LeMone, 1989; Stith et al., 2002). The remaining large supercooled cloud and rain drops freeze readily a short distance (less than 1 km) above the 0°C isotherm level (Black and Hallett, 1986). The new approach to weaken hurricanes by seeding with submicron hygroscopic aerosols was submitted on April 2006 as a proposal to the Yeshaya Horowitz Association, and filed as a provisional patent in early 2007. This alternative approach was developed further in this study based on the observations mentioned above as well as on the results of numerical simulations (Khain et al., 2005; Lynn et al., 2005, Van den Heever et al., 2006) indicating that an increase in the concentration of small aerosol particles (AP) leads to the formation of a great number of small droplets with low collision rates. The delay in the raindrop formation and rainout from the lower parts of the clouds leads to a greater amount of water advected to above the 0°C isotherm, where freezing occurs mostly below −10°C (Rosenfeld, 1999 and 2000; Rosenfeld and Woodley, 2003; Andreae et al., 2004). This results in at least partial suppression of raindrop formation in the lower parts of the clouds and to additional latent heat release at high levels because of drop freezing and extra water vapour condensation on droplets and ice particles. Consequently, clouds developing in a polluted atmosphere turn out to be more intense and reach higher levels than clouds developing in a less polluted air mass. The melting of the ice hydrometeors at lower levels causes enhanced cooling and downdrafts that can trigger new convective elements. This convective invigoration effect was proposed in Williams et al. (2002), described by Rosenfeld (2006 and 2007), observed by Koren et al. (2005), Myhre et al. (2007) and Lin et al. (2006), and simulated by Khain et al. (2004 and 2005), Lynn et al. (2005) and Van den Heever et al. (2006).

These observational and numerical results indicate a possibility of mitigating tropical cyclones (TC) by seeding the air that is ingested into the cloud bases with large concentrations (1000–2000 cm^{-3}) of small (0.1 to 0.2 μm diameter) cloud condensation nuclei (CCN). It was proposed that the expected convective invigoration at the hurricane periphery should decrease the influx of air mass to the hurricane center and decrease, therefore, the ascending vapour mass and the latent heat release in the eyewall. That is, seeding of small CCN to suppress warm rain (Fig. 1D) in hurricanes could lead to a relative weakening of the storm, at least initially. This is because the seeding should increase the warming aloft (Figs. 1E and G) and evaporative cooling at the lower levels (Figs. 1C and H).

This conceptual model was tested using a two nested grid

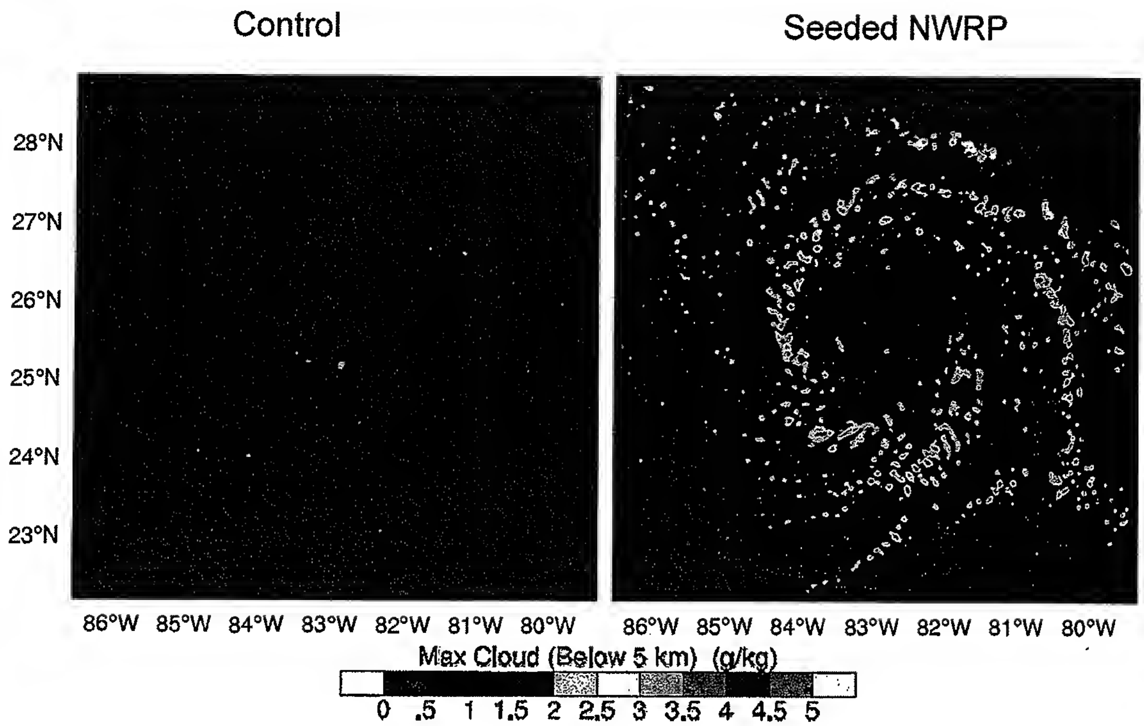

Fig. 2. Maximum cloud water contents in clouds of "natural" and "seeded" hurricane runs at 27 July 2005 18:00 UT. "Seeding" leads to a significant increase in mass of cloud water reaching supercooled levels, especially at the storm periphery.

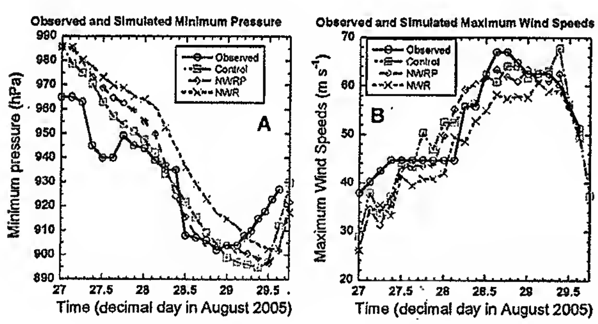

Fig. 3. Time dependence of minimum surface pressure **(A)** and maximum wind speed **(B)** in three simulations: Control warm rain (WR) marked red, NWR (no warm rain allowed) marked green and NWRP (no warm rain allowed at the TC periphery) marked blue. The observed values of Katrina are shown by the thin black line. The deviation of pressure in the numerical simulations from that in real Katrina can be attributed by inexact assimilation of initial data in the model.

Weather Research Model (WRF: Michalakes et al. (2005), Skamarock et al. (2005), Michalakes et al. (2001)) by simulating the evolution of hurricane Katrina during 27–29 August 2005. Given this focus of the exploratory study, the simulations are purposely crude, where warm rain processes are set completely on or off at the periphery, in order to reveal the greatest possible aerosol effects on hurricane peak intensity (minimum pressure, and maximum winds) and overall strength (radius of area covered by hurricane force winds and wind speed outside of the radius of maximum wind). The paper also discusses some new physical insights that result from an analysis of the three-dimensional temperature, humidity, and cloud fields.

Cotton et al. (2007) also simulated the possible impacts of CCN seeding of hurricanes. They simulated the evolution of an idealized TC starting with a weak initial vortex using the Regional Atmospheric Modeling System (RAMS) model (Cotton et al., 2003) with a two moment microphysical scheme (Saleeby and Cotton, 2004). The TC was simulated at 2 km horizontal resolution. The seeding effect was simulated by adding 1000 or 2000 CCN cm^{-3}, compared to the natural background of 100 cm^{-3}. The TC developing in dusty air was substantially weaker at the mature stage compared to the storm developing in the clean air, with peak winds lower by 25 ms^{-1} and central pressure higher by 25 hPa. Adding giant CCN that restored the warm rain, however, eliminated most of the TC weakening.

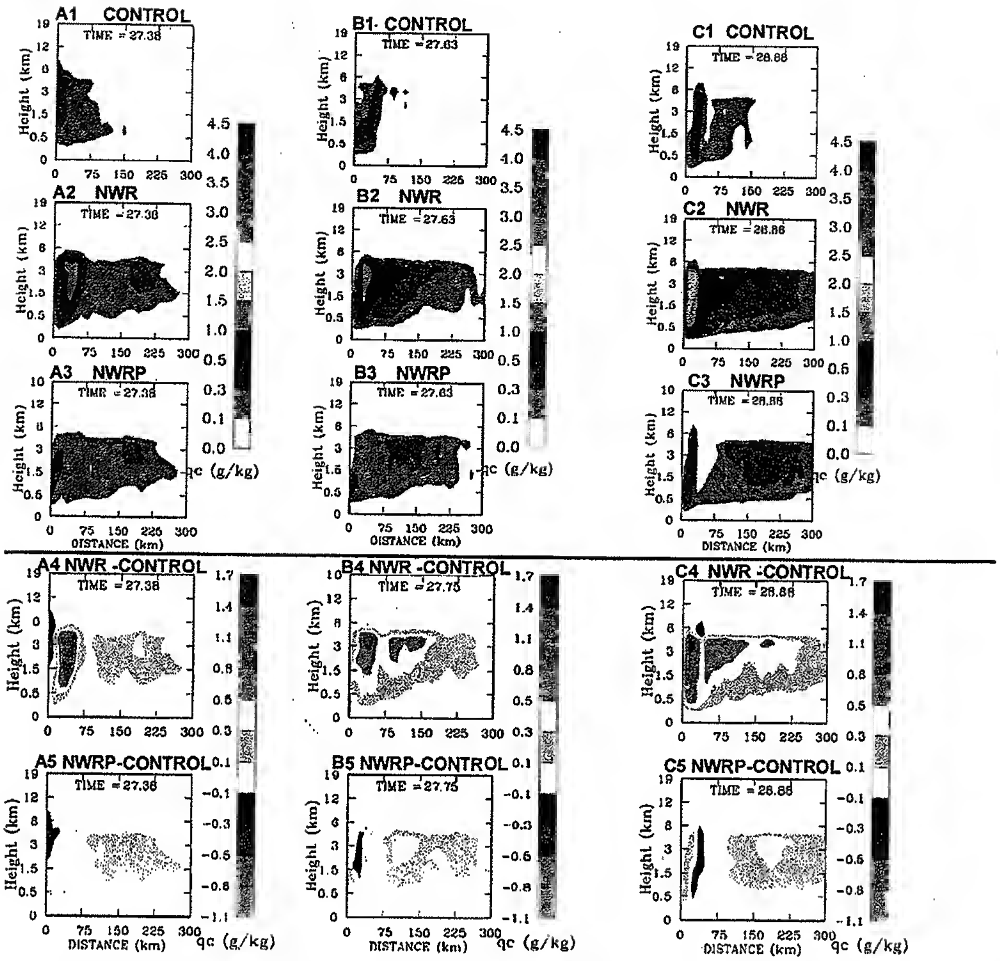

Fig. 4. (a) Vertical-radial cross sections of the azimuthally averaged cloud water content (CWC) in three simulations at different time instances (upper panels) and the differences of CWC between the NWR and NWRP on one hand and control (WR) simulations. The panels are marked by letters (A, B, C) denoting different time instances and by the times in decimals of day.

2 Design of the numerical experiments

A two nested grid of the Weather Research and Forecasting Model (NCAR WRF ARW version) was used to simulate Hurricane Katrina from 27 August 0z to 30 August 0z. The available computer resources (a 16 processor Linux cluster) were enough to simulate resolutions for the finest and the outer grid of 3 km and 9 km, respectively. The bulk-parameterization by Thompson et al. (2004) was used in the cloud-resolving simulations on both grids, while the coarse grid used both the bulk microphysics and the Kain-Fritsch cumulus convective scheme (Kain and Fritsch, 1993).

The WRF initial conditions were obtained from the Global Forecast System (GFS) Reanalysis data with a grid resolution of 30 km. The analyzed reanalysis fields were used "as-is" to create the initial hurricane vortex. The vortex developed within several minutes of simulation time into a hurricane. The atmospheric lateral boundary conditions of simulation were updated every three hours using GFS Reanalysis data. The sea surface temperatures were obtained from the Global Forecast System analysis data file for 00:00 UT 27 August.

The natural or control run, aimed at simulating the actual conditions in Katrina, allowed for warm rain (WR) formation by drop-drop collisions. The effect of sub-micron hygroscopic aerosols on warm rain processes was simulated in two other runs. Since small aerosols lead to the formation of a great number of small droplets with very low ability to form raindrops, the aerosol effects in the "seeding" runs were parameterized by shutting off the drop-drop collisions. In the first experimental simulation named "No Warm Rain" (NWR), the warm rain formation was shut off over the entire TC area. The NWR represents the "reference" simulation carried out under idealized conditions, which cannot occur in real hurricanes, because wind driven sea spray particles serve

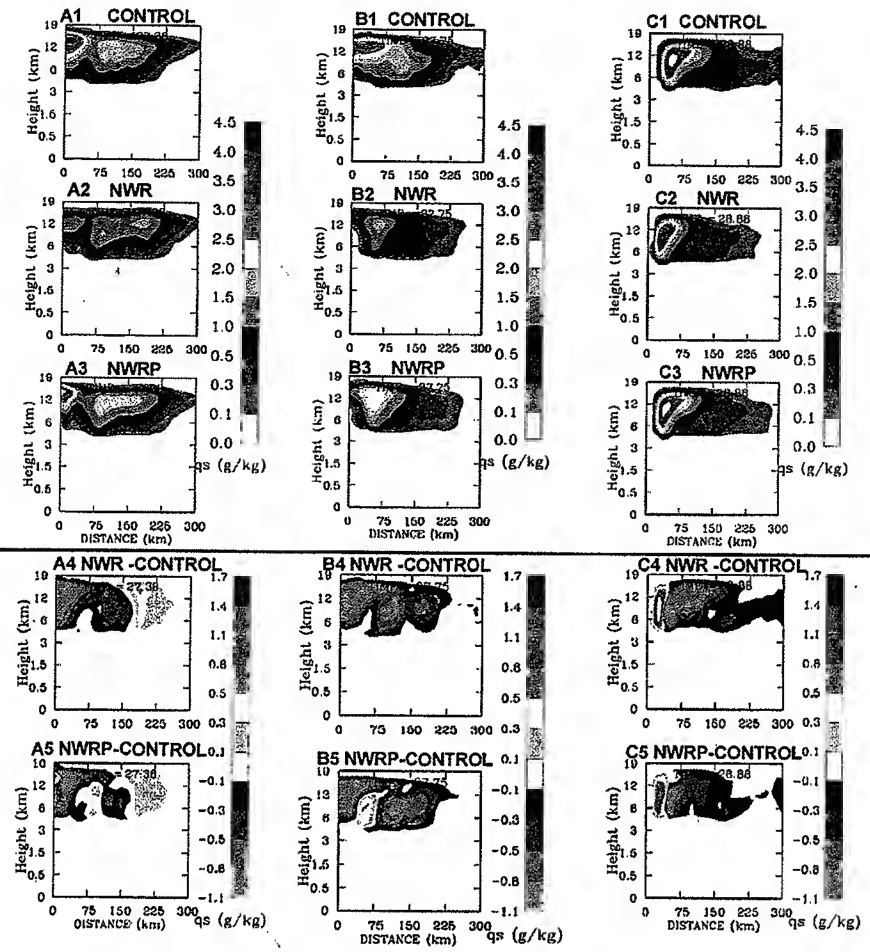

Fig. 4. **(b)** The same as in Fig. 4a, but for ice content.

as giant CCN (>1 μ m diameter) that initiate early rain even when large concentrations of small CCN exist (Woodcock, 1953, Segal et al., 2004). Woodcock (1953) measured, just below cloud base of clouds of a tropical cyclone near Florida, 10 μ m diameter wet sea spray particles at a concentration of $1\,cm^{-3}$ under hurricane force winds ($32\,ms^{-1}$). The concentration of 22 μ m sea spray particles was $0.3\,cm^{-3}$, and 47 μ m particles at $0.1\,cm^{-3}$. Such concentration of ultra-giant CCN should overwhelm the rain suppression seeding effect even in clouds with very small drops.

The second experimental simulation, referred to as No Warm Rain at the Periphery (NWRP), tests the impact of seeding aerosols only on the hurricane periphery, where the surface wind was smaller than $22\,m\,s^{-1}$. This threshold is near the lower bound of Beaufort 9 wind, which is defined at sea by "*spray may affect visibility*." The presence of high concentrations of sea spray would most likely render ineffective any seeding of clouds with large concentrations of small CCN. Hence, warm rain is turned off only in that part of the hurricane that has winds speeds less than the threshold value.

Figure 2 illustrates the effect of turning off warm rain processes on cloud liquid water content in the NWRP run compared to the Control (WR) run. One can see a dramatic increase in the LWC in clouds at the periphery of the seeded hurricane, in response to turning off the warm rain collision processes. Such an increase is consistent with past work using more sophisticated models (Khain et al., 2004, 2005; Lynn et al., 2005a, b; among others). In situ, this can be explained by the slower transformation of cloud droplets to raindrops in polluted clouds that occurs because polluted clouds create many small droplets which are too small to collide and coalesce efficiently.

3 Results

The simulated data were saved every three hours. The track of the simulated storms each curved to the north at an earlier time than the observed Katrina, and each made landfall about

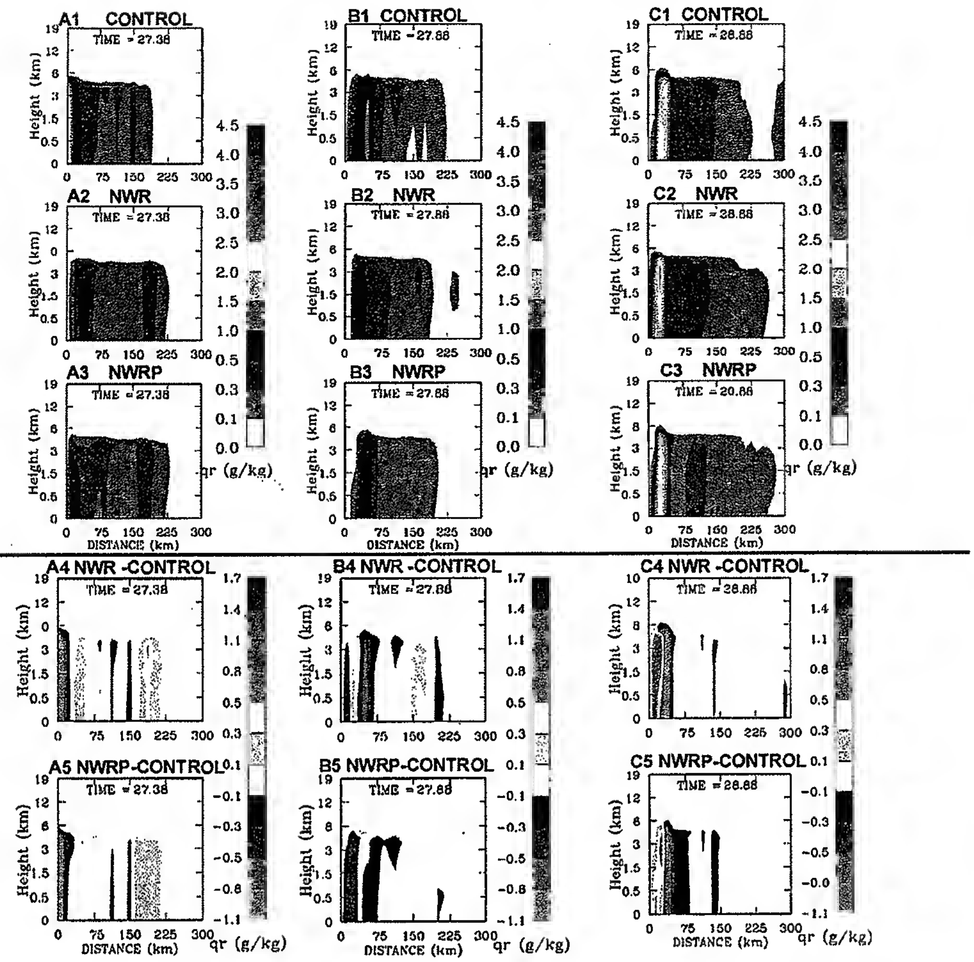

Fig. 4. (c) The same as in Fig. 4a, but for rain water content.

200 km to the east of actual landfall of the observed storm (not shown). Nevertheless, the model was able to reproduce the main features of the hurricanes evolution, including the formation of the super hurricane with the minimum pressure of about 900 hPa (Fig. 3). For instance, Figs. 3a and 3b show the simulated surface minimum pressure and maximum wind speeds, which are compared to the three hourly observational data from the National Hurricane Center. Within three hours of simulation time, the modelled Katrinas had reached hurricane intensity with maximum wind speed greater than $32.5\,\mathrm{m\,s^{-1}}$ and with minimum surface pressure of at least 965 hPa (Fig. 3a), The simulated maximum winds then approach the observed values and then quite closely agree with observations after about 15 h of simulation time (Fig. 3b). Within the first 24 h, the simulated minimum pressures were less than the control run in both NWR and NWRP. However, after this time the simulated minimum surface pressures in NWRP are less than in the Control run, with a concurrent increase in maximum wind speed. In contrast, the simulated minimum pressures and maximum wind speeds in NWR remain higher and less than the control values.

Figure 4 shows vertical cross sections of azimuthally averaged fields of cloud water content (CWC), rain water content (RWC), cloud ice, temperature, pressure, relative humidity, radial and tangential wind components, which are presented for each of the simulations at the times t=27:09, 27:18 and 28:21 (day in August 2005: hour UT). In each simulation, the model reproduced the typical structure of a TC with an eye wall with strongly precipitating clouds, a warm core with negative vertical velocity in the TC eye, and the inflow layer in the lower and outflow layer in the upper troposphere. The radius of maximum winds varies between 30 and 50 km from the center. According to Fig. 4a the cloud water content increased in the NWRP compared to Control, and further increased in the NWR simulation. By 24 h (t=28:00) the changes in the TC structure caused by warm rain prevention are remarkable. The main changes in microphysical structure are: the increase in CWC within the radial range annulus of

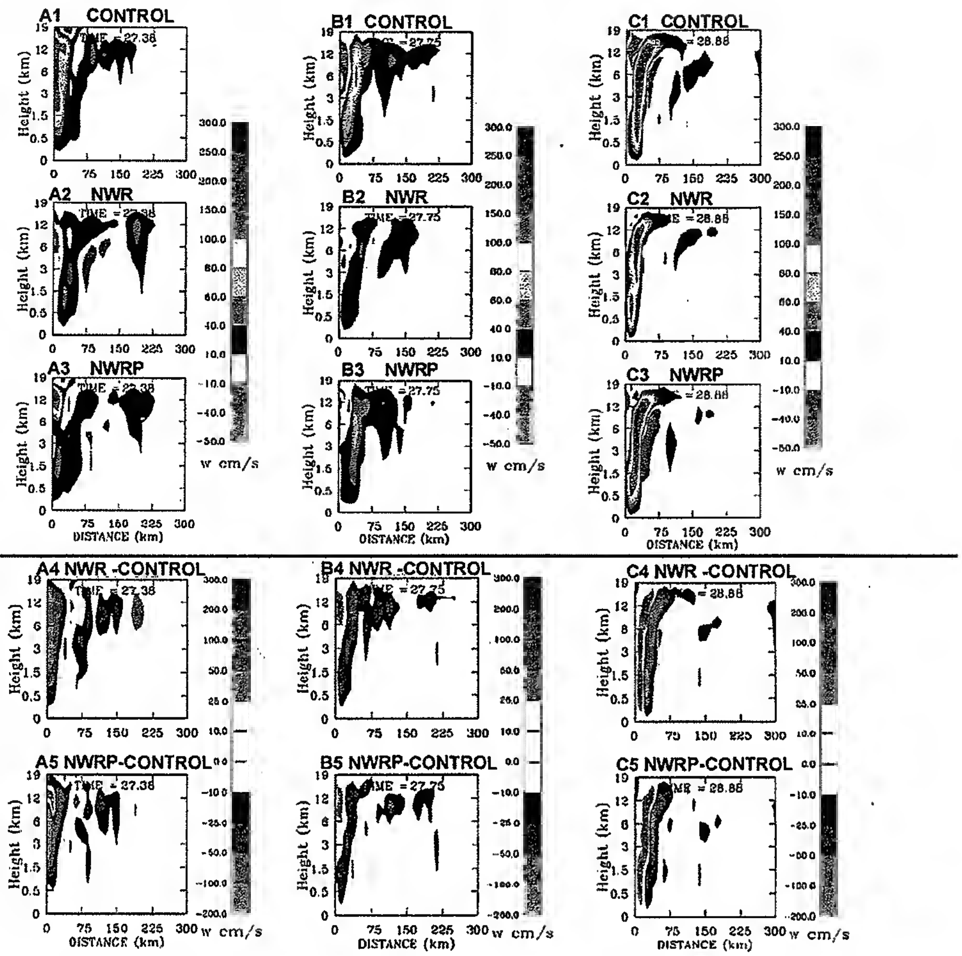

Fig. 4. (d) The same as in Fig. 4a, but for vertical velocity.

100–300 km (Fig. 4a panel B5) and a corresponding decrease in rain water content (Fig. 4c panel B5). The spreading of the zone of enhanced CWC toward the TC center is caused by the radial TC circulation (Fig. 4e).

During the first 12 h, the deep convection at the periphery in NWRP is invigorated (Fig. 4d panel A5), produces more ice at the periphery (Fig. 4b panel A5), precipitates more (Fig. 4c A5) and warms the upper levels (Fig. 4g A5) than in the control. The increase in the updraft at the TC periphery decreases the influx of the air mass to the TC center by more than $5\,\mathrm{m\,s^{-1}}$ (Fig. 4e A5), leading to the weakening of the TC convection at its center, and the weakening of the TC maximum tangential wind by about $5\,\mathrm{m\,s^{-1}}$ (Fig. 4h panel A5) in NWRP relative to that in the control run. Suppressing warm rain everywhere in the NWR run had stronger effects in the same directions (panels A4 at the same figures). The area of strong winds also decreases significantly during the first 24 h (Fig. 5 panels A and B). The maximum difference in minimum TC pressures in NWRP compared to the Control simulation (WR) of ~10 hPa is reached at about t=28:00 (i.e. 28 August 2005 00:00 UT), which is 24 h after the seeding run started (see Fig. 3a).

Note that the suppression of warm rain results in significant changes in the thermodynamic structure of the TC. The main thermodynamic changes are: the decrease in temperature at the low levels at the TC periphery and within the TC eye wall (Fig. 4g panels B5 and C5) for the NWRP run as compared to those in the natural TC (Control run). The decrease at the TC periphery is caused by the enhanced evaporation due to the added amount of cloud water that is less effectively precipitated due to its reduced droplet size. This leads to a corresponding increase in the air humidity (Fig. 4f panels B5 and C5) and decrease in temperature (Fig. 4g panels B5 and C5). A decrease in temperature at the TC center occurred only in the NWR simulation, where warm rain was suppressed also in the eyewall.

After 36 h the eye of the NWRP run contracted as shown by the radius of peak winds (Fig. 5 panel d; Fig. 6) and the

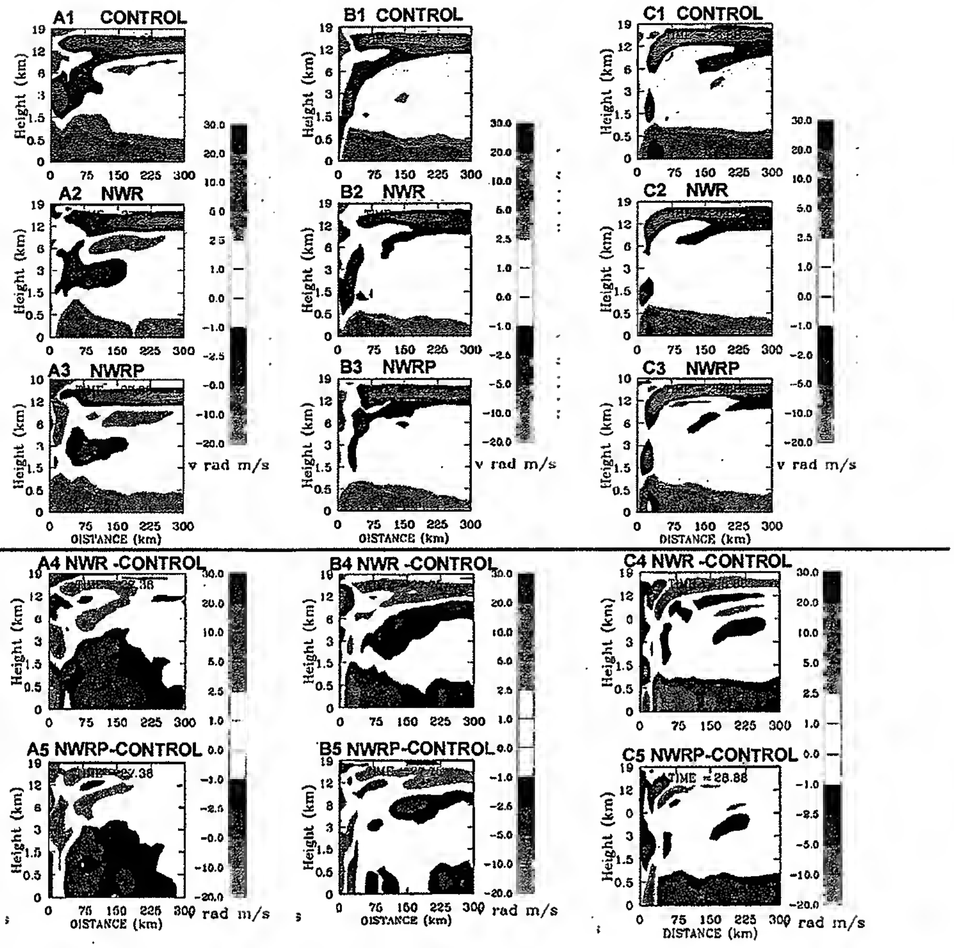

Fig. 4. (e) The same as in Fig. 4a, but for radial velocity field.

central pressure correspondingly decreased (Fig. 3b). At the same time the pressure increased outside of the eye wall. This is manifested as enhanced pressure gradients at the eye wall that leads to intensification of the winds at radial distances less than 30 km while weakening the winds outside the eye wall, when comparing the NWRP to the Control runs (Fig. 4h panel c5 and Fig. 5 panel d). The relation of the eye diameter to the extent of suppression of warm rain is evident in Figs. 5 and 6, where the peak winds that mark the location of the eyewall occur at progressively smaller radial distances from the TC in the runs with respectively greater suppression of warm rain from the Control to NWRP and NWR simulations. At larger distances from the hurricane center, the wind speed weakens with the progressive suppression of warm rain (see Fig. 7). In fact, the decreasing wind speed from Control to NWRP and NWR at the periphery of the TC is compensated near the center of the TC by the increasing peak wind speeds due to the shrinking of the eye.

4 Interpretation of the results

The initial result of suppression of warm rain is warming at the upper levels due to the added release of latent heat of freezing (Pathway E of Fig. 1) and enhancing the updrafts aloft, coupled with low level melting and evaporative cooling (Pathways C and H of Fig. 1). As was shown by Khain et al. (2005), this is the typical response of maritime convective clouds to suppression of warm rain due to added large concentrations of small CCN. However, about 12 h after the initial "seeding" (i.e. suppression of warm rain), the upper level warming became limited to a shallow layer above the freezing level (Fig. 4g) and the enhanced updrafts aloft vanish (Fig. 4d) in the NWRP and NWR runs. Yet, the low level cooling remains at least as strong. The enhanced low level relative humidity (Fig. 4f) implies that this low level cooling occurs due to greater low level evaporation of cloud water that was not precipitated, i.e. moving energy from pathway D to pathway C in Fig. 1. This means a net loss of condensation

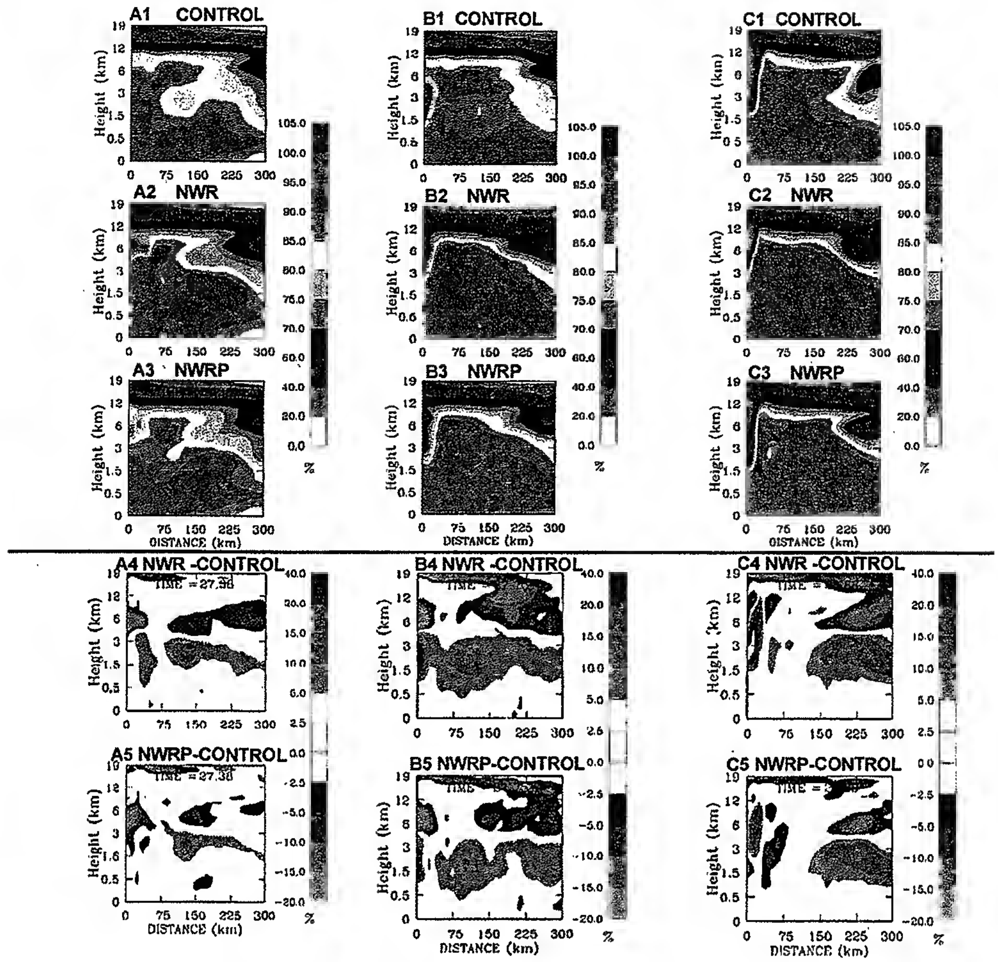

Fig. 4. (f) The same as in Fig. 4a, but for the relative humidity.

latent heating, which leads to less buoyant lower tropospheric air. This is why the evaporative cooling at low levels in the NWR and NWRP cases reduces the deep convective ascent, causing the air to advance closer to the circulation center before eventually being forced to rise. This causes the eye to be more compact. The equivalent potential temperature does not change in the process of evaporation of cloud water. Therefore, when this cooler air is forced to rise it can still form intense deep convection at the eye wall. Based on these considerations, it is suggested here that the continuous cooling at the TC periphery (Fig. 4g panel C5), especially in the TC lowest 3 km, leads to compaction of the TC circulation which can be attributed to the lesser tendency of the more stable low level air to rise before reaching the circulation center. This is supported by the NWR run that has the strongest low level cooling of the three simulations (Fig. 4g panels A4, B4 and C4) associated with the greatest extent of suppression of warm rain. The less buoyant low level air supposedly delays rising until it more closely approaches the hurricane center, reducing the radius of the eye even more (see Fig. 6). This idea is also supported by the simulation results of Nong and Emanuel (2003), who showed that low level air with enhanced buoyancy tends to rise before reaching the eyewall and initiate the process of an eyewall replacement with a larger eye (Houze et al., 2007). The buoyancy was enhanced in that simulation by increasing the low level relative humidity *without* a corresponding decrease in the temperature.

When preventing warm rain also in the center with the NWR run, the intense evaporative cooling takes place within the eye as well (Fig. 4g panels B4, C4), so the temperature gradient is not as strong and the central pressure of the TC is higher as compared to that in other simulations at all times. Consequently, the TC in the NWR run has the largest central pressure, has weakest peak winds and smallest areal extent of hurricane force winds compared to the other simulations (see Figs. 3, 5–7). At 29:00, near the time of the lowest minimum pressure, the radius of the area covered by hurricane force

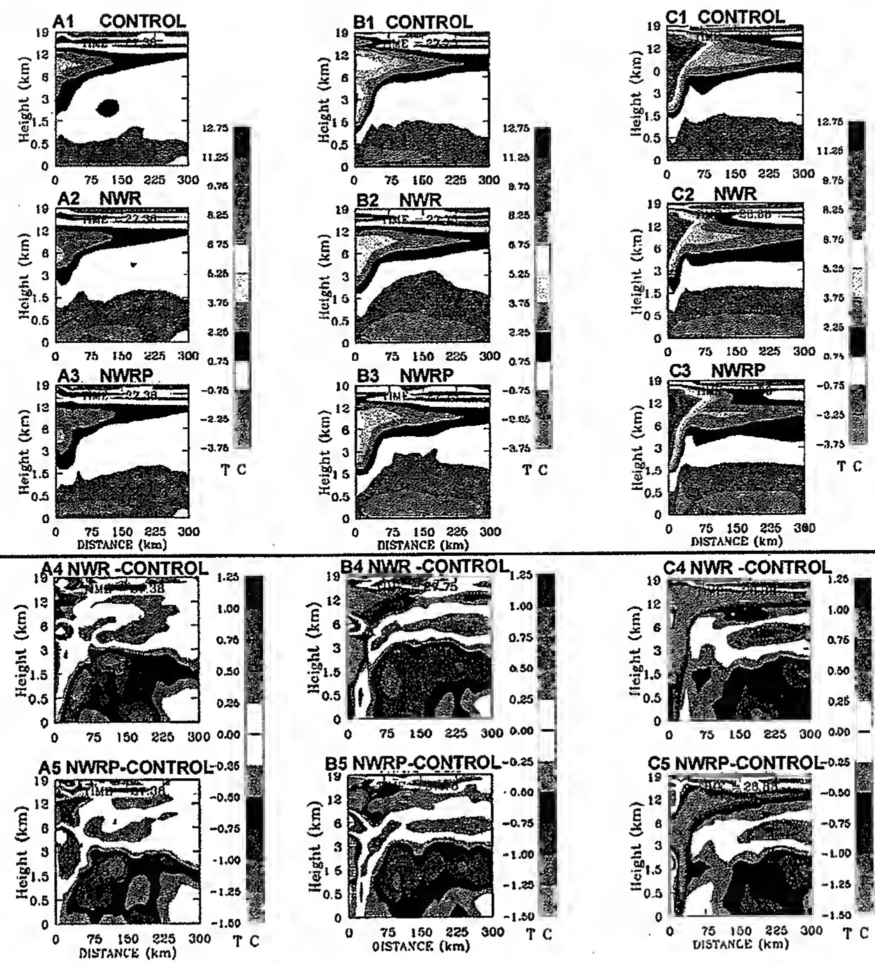

Fig. 4. (g) The same as in Fig. 4a, but for the temperature field.

winds was 108 km for the control run, 80 km for the NWRP run and only 62 km for the NWR run (see Fig. 5f). The radius of maximum winds, which is the radius of the eyewall ring, is not well correlated with the maximum wind intensity, which occurs at the eyewall. There are super hurricanes with large eyes and minimal hurricanes with small eyes. In this particular case (see Fig. 5) the progressive suppression of warm rain from Control to NWRP and NWR reduced the radius covered by hurricane force winds (Fig. 7), but at the same time reduced the radius of the eye (Fig. 6). This contraction of the eye compensated the peak winds in the eyewall for the overall weaker winds in most of the area of the hurricane outward of radial distance of 40 km from its center. As already suggested here, this relation between the overall TC strength as defined by the radius of hurricane force winds and the compaction of the eye appears to be related to the weakening effect of the low level evaporative cooling. This cooling decreases the tendency of air to ascend until it reaches closer to the circulation center and so shrinks the eye. It should be noted, however, that TCs often undergo periodic changes in the radius of the eye and the respective peak winds for reasons that cannot be related to aerosols (Houze et al., 2007). Fluctuations in the radius of the eye, not necessarily due to an eye replacement cycle, may explain the fluctuations in the observed intensity of Katrina shown in Fig. 2.

The proposed mechanism of low level evaporative cooling due to the suppressed warm rain might explain the strong reduction of the TC intensity in the simulations that did not take sea spray aerosols into account (Cotton et al., 2007), which is similar to the NWR simulation here. It can also explain why adding giant CCN that enhance warm rain attenuated the weakening effect in that simulation. Unfortunately, insufficient information is provided in their publication for confirming this possibility.

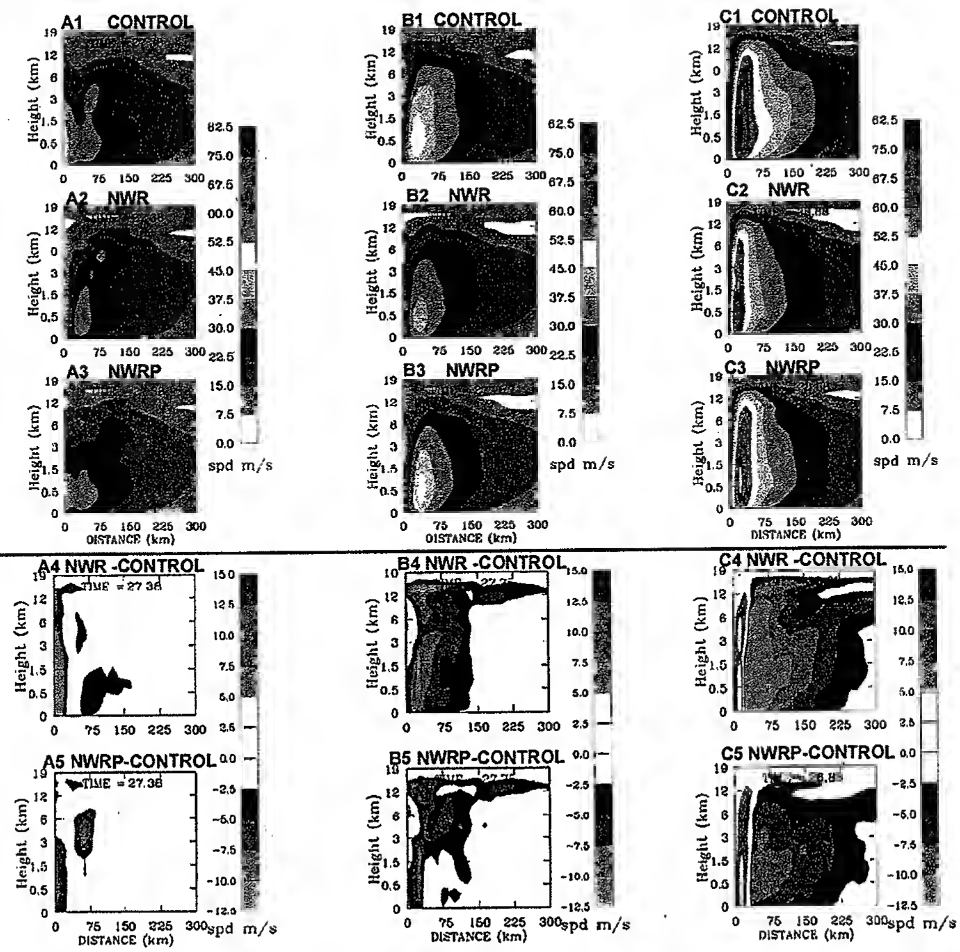

Fig. 4. (h) The same as in Fig. 4a, but for the tangential velocity.

5 Discussion and conclusions

The main result of the simulations is that tropical cyclone intensity and structure are apparently sensitive to aerosol concentrations. Physical arguments and numerical simulations indicate that it may be possible to decrease the area covered by hurricane force winds in a TC by injecting small aerosol particles into the air that is ingested into the bases of clouds located on the TC periphery 200–400 km from its center. In the simulated case the wind speed was decreased by seeding during the whole period of simulations at radial distances r>40 km (i.e over the huge area exterior to the eye wall). The low level cooling causes also a contraction of the eye and hence the relative intensification of the eyewall winds, occasionally even matching or exceeding the peak wind intensity of the control simulation. Storm surge is caused by the mean wind over large areas and not by the maximum wind over very small zones. Therefore, even in the cases when peak winds at the eyewall are not reduced, if the seeding leads to a decrease of wind speed over most of the area of hurricane-force winds and decreasing its areal extent as shown in Fig. 7, it would be an important result.

This provides the basis for seeding experiments, which are practical because wind speeds at distances greater than 200–400 km from TC centers are weak even in very strong hurricanes, which allows operative flights. The following calculations of the relevant orders of magnitudes show that this might be a practical endeavor. Seeding 1 kg of hygroscopic particles having diameter of 0.1 μm and density of 2000 kg m^{-3} can fill homogeneously 1 km^3 with a concentration of nearly 1000 particles cm^{-3} (10^{18} particles dispersed in 10^{15} cm^3). If the seeding is applied around the storm into the converging marine boundary layer that feeds the storm clouds, the seeding rate should be matched to the influx rate. With average inward radial winds of 5 ms^{-1} at the 0.6 km deep boundary layer (see Fig. 4a) along the nearly 2000 km circumference of the radial distance of 300 km the influx of 60 km^{3}s^{-1}. This corresponds to a seeding rate of 60 kg s^{-1},

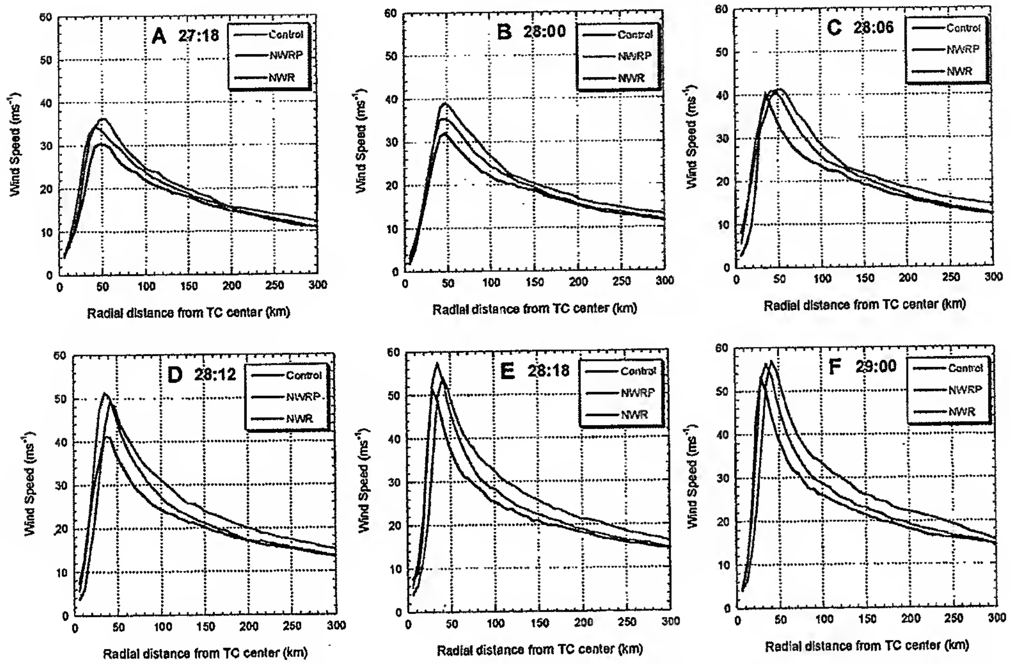

Fig. 5. The simulated radially averaged wind speed of the Control warm rain run, No Warm Rain in the Periphery (NWRP) run, and No Warm Rain (NWR) run, during the evolution of the hurricane. Note the decreasing wind speed from Control to NWRP and NWR and the opposite effect of increasing peak wind speeds due to the decreasing radius of the eye.

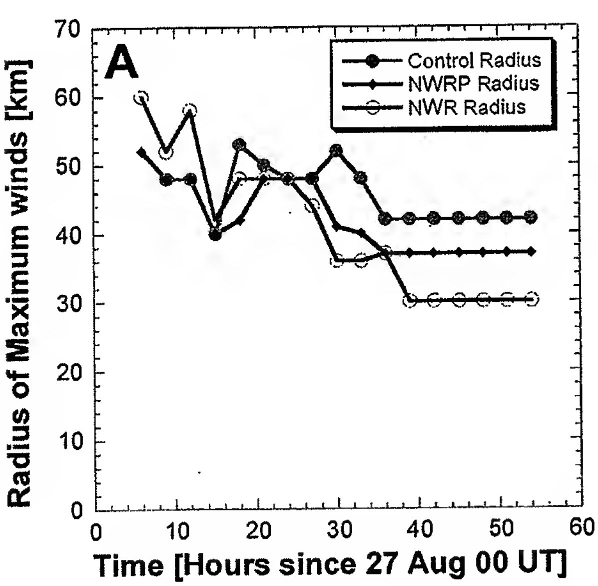

Fig. 6. The radius of the eye for the three simulation experiments. Note the smaller radius of the eye for greater extent of suppression of warm rain, going from the full warm rain control run (WR) to the no warm rain in the periphery (NWRP) and to the fully suppressed warm rain everywhere (NWR).

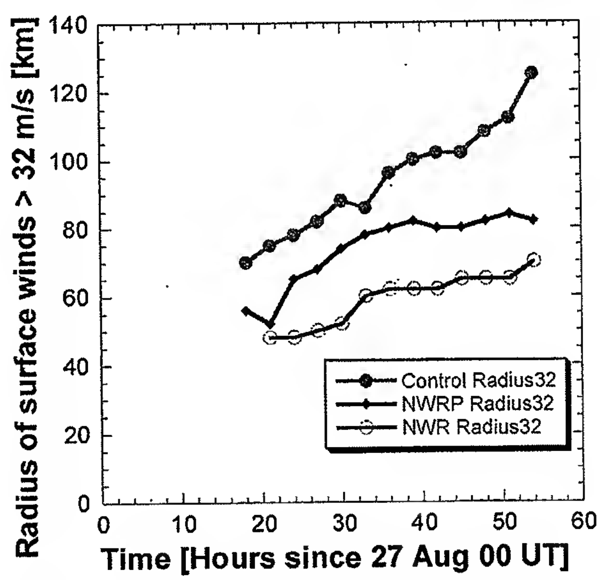

Fig. 7. The radius of the area with hurricane force winds. Note the smaller radius of area with hurricane force winds for greater extent of suppression of warm rain, going from the full warm rain control run (WR) to the no warm rain in the periphery (NWRP) and to the fully suppressed warm rain everywhere (NWR).

or 216 ton per hour. As far as delivery capacity of the necessary mass of particles is concerned, this seems to be practical with large cargo airplanes having payloads exceeding 100 tons.

This means that seeding the full depth of the marine boundary layer with 0.1 μ m hygroscopic particles at concentrations of several thousands particles cm^{-3} is practical at the storm scale. It can be done by dispersing hygroscopic smoke from 5 to 10 cargo airplanes flying in the boundary layer just outside the TC spiral cloud bands so that the particles would be drawn into the storm by the low level convergence after having sufficient time to mix well in the boundary layer.

The apparent susceptibility of the vigor of tropical maritime clouds to small CCN seeding opens the possibility of changing not only the TC intensity, but also its track. Since the tangential velocity (which is orthogonal to the radial velocity) at the radial distances of 50–300 km in the NWRP seeded TC is smaller than that in the control run, the seeded TC moved more eastward due to the beta effect (e.g. Fiorino and Elsberry, 1989; Falkovich et al., 1995) and made landfall ~50 km farther to the east than the non-seeded TC. Being the weakest, the TC in the NWR run shifted eastwards from the control TC even more (see Fig. 8). In addition, TCs tend to move into the zone of the most developed convection at their periphery (e.g. Falkovich et al., 1995).

These simulations demonstrate that the ability to affect tropical storms is greatest in their organizational and early stages. The seeding window gradually closes with the intensification of the storms, mainly due to the expansion of the wind induced sea spray that enforces warm rain to greater radial distance from the center of the storm. The size of the seeding window in the simulation includes the convective clouds that occurred at radial distances with winds smaller than $22\,ms^{-1}$. According to the combined information in Figs. 4a and 5 this area included the ring of outer 150 km of the clouds at t=18 h, more than 100 km into the hurricane at t=36 h, and at least 50 km from the outer edge of the hurricane low clouds at t=48 h, which was the time of peak intensity.

The simplification of the modeling of the seeding effect has to be taken into account in the interpretation of the results. On the one hand, it is hardly possible to prevent warm rain formation from maritime clouds under simulation of realistic aerosol particle concentrations. However, both remote sensing (Rosenfeld, 1999; Rosenfeld and Woodley, 2003) and in situ (Andreae et al., 2004) observations of tropical clouds interacting with smoke from forest fires demonstrate that warm rain can be shut off entirely in some circumstances. Thus, the simplification indicates the maximum possible effect that could be realized using high aerosol particle concentrations. On the other hand, the utilization of the 3 km model resolution did not make it possible to resolve the clouds with characteristic scales below about 10 km, which is especially important for clouds at the TC periphery. Besides, the crude resolution significantly decreases the vertical velocities and depths of resolved clouds (Khain et al., 2004). More simulation work with cloud models that address cloud microphysical processes explicitly and the interactions with sea spray aerosols must be done before field experiments can be considered. In any case, the best prospects are in seeding that is aimed at affecting the initial organization and track of the storm. If this study will eventually progress to actual seeding experiments, detecting the seeding effects will be a challenge on the background of natural variability due to changing sea surface temperature and other natural processes. Such experiments will need to be carefully designed along with detailed simulations to yield conclusive results.

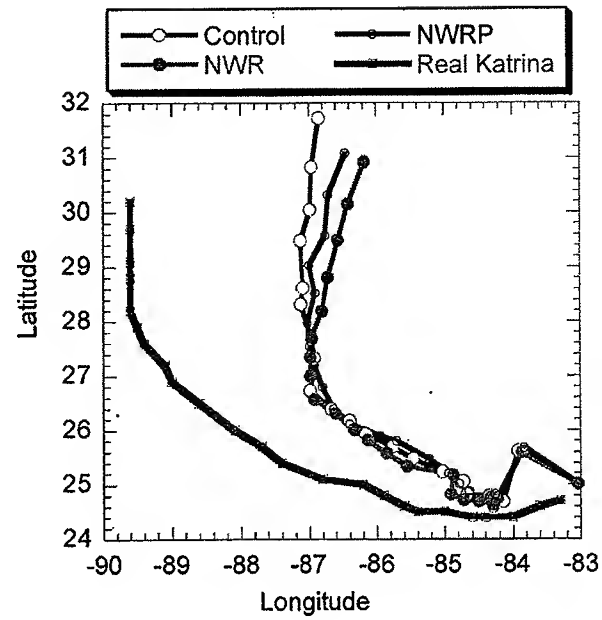

Fig. 8. Time tracks of the observed and simulated hurricane for the Control run with full warm rain, NWR (no warm rain allowed) and NWRP (no warm rain allowed at the periphery). Note that the suppression of warm rain diverts the track eastward.

Acknowledgements. This study was supported by the European Community–New and Emerging Science and Technologies [Contract No. 12444 (NEST)–ANTISTORM].

Edited by: J. Quaas

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re application of: Ronald D. BLUM, ET AL.	Confirmation No. 9812
Application No.: 09/994,860	Examiner: Boeckmann, Jason
Filed: November 28, 2001	Technology Center/Art Unit: 3752
For: METHOD AND APPARATUS FOR REDUCING THE INTENSITY OF HURRICANES AT SEA BY DEEP-WATER UPWELLING	
Customer No.: 20350	

Mail Stop AF
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

DECLARATION UNDER 37 C.F.R. § 1.132

I, Captain Neil E. Rondorf (United States Navy, Retired) declare the following:

1. I am Assistant Vice President of Science Applications International Corporation headquartered in LaJolla, California with east coast headquarters in McLean, Virginia.

2. I hold a Bachelor of Science degree in Oceanography from the U.S. Naval Academy, a Master's Equivalent in Nuclear Engineering from the Naval Nuclear Power Program, and a Master's Equivalent in International Relations from the Naval War College. I have over 25 years of management and technical engineering of Navy programs including shipboard operations and Integrated Undersea Surveillance System programs. A copy of my resume is attached as Exhibit A.

3. I have been retained by the assignee of the above-identified application to assist in responding to the Office Action. I have no financial interest in the assignee or the outcome of this patent application, including whether it issues as a patent or not. I am being compensated for the time spent on this matter at the rate of $200/hr, plus reasonable expenses.

4. I have read and am familiar with the above-referenced application. I have also read and am familiar with the Office Action mailed May 4, 2007 ("Office Action") pertaining to this application.

5. It is my understanding that the claims currently under examination, which relate to, *inter alia*, methodologies for reducing the intensity of a hurricane, were rejected as allegedly being wholly inoperative, lacking credible utility, and not enabled. Specifically, the Examiner asserts:

> ...applicant admits in his arguments, "submersibles of the kind required for this application do not presently exist." It seems that applicant wishes that someone will come along and develop the technology required to make the required submersibles, thereby enabling the present invention. Therefore, it is impossible for one of ordinary skill in the art at his time to make and or use this invention. Office Action at page 6.

6. This Declaration provides support that the type and number of submersibles needed for implementing the claimed invention may be readily ascertained by using the amount of direction provided for in the specification and the knowledge of one skilled in the art at the time of filing the application without any undue or unreasonable experimentation. In particular, the specification is replete with the detailed description of various gas sources (*see, e.g.*, para 0029), submersible designs (*see, e.g.*, para 0034), inception strategies (*see, e.g.*, 0026-27, 49-64), and the exemplary calculation for upwelling volume required for successful surface water cooling (*see, e.g.*, 0049-64).

7. During my experience of new construction on USS Indianapolis (SSN-697), I became very familiar with submarine construction. In addition, during my tour as Commanding Officer

of USS Minneapolis-St Paul (SSN 708), I conducted a 12 month conversion period in Portsmouth Naval Shipyard. During this time, I became intimately familiar with shipyard conversion methodologies. Based on this experience and construction methods available on or before November 28, 2001, the modification of exiting submarine hulls or construction of a towed body to carry and release a desired amount of gas to produce an upwelling was well within both design and industrial capacity and could have been implemented in a straight forward manner.

8. Submarines may be converted to a gas carrying capacity by two methods. The first conversion method is the modification of existing submarine hulls. The most favorable submarine choices for conversion to a gas carrying capacity would be the Russian Typhoon Submarine and the US Trident Missile Submarine. Indeed, the conversion of submarine missile load capacity to other uses is a proven technology that has been executed by the United States industrial capacity. For example, using technology available on or before November 28, 2001, the Navy began a submarine conversion in November 2003 and completed converting the first submersible ship ballistic missile (SSBN) hull to a submersible ship guided missile (SSGN) hull and was completed December 2005. Here, the missile tubes were converted for use as conventional missile launcher. In addition, inserts were developed to fit inside the former missile tube yielding an alternative mission payload capacity. The converted tubes for alternative payloads are designed to equalize with the pressure of the sea and allow the deployment of the payload with the upper hatch open and no pressure differential. Thus, the bubble method for gas release would be very compatible with this operating concept. This conversion is a matter of record in Department of Defense program documents. The conversion is described in detail in the reference from the Commander Submarine Force web site attached as Exhibit B.

9. The second submarine conversion method involves cutting the submarine hull in half and inserting a new section specific for the desired use. The United States and Russia have successfully converted submarine hulls from one use to another using this approach on or before November 28, 2001 and could have been implemented in a straightforward manner. Therefore,

the conversion of an entire section of a submarine from its original use to a gas release volume is entirely within the capacity of shipyards within the United States and other developed industrial nations. The normal bulkhead construction allows for watertight integrity in each compartment in order to allow the compartment to be isolated in the event of flooding. Thus this design technique can be used to provide pressure isolation to the proposed gas volume hull section. Using this approach, the Typhoon hull form would be the preferred choice for conversion to a gas carrying capacity.

10. As an alternative to submarine conversion, a towed body may be readily constructed to carry and release the gas required for upwelling. The towed body would be a simplified submersible that could be entirely constructed using submarine construction methodologies available on or before November 28, 2001. If the towed body is unmanned, the majority of the body's volume may be dedicated to gas carrying capacity with minimum on board systems such as depth control, minimum propulsion, and gas storage and release systems. The existing Naval Research vessel NR-1 is an example of a towed body application and has an estimated volume as a towed body of approximately 32,400 ft^3. The existing submersible can be easily scaled up to increase gas carrying capacity.

11. The towing of submerged bodies or the towing of surfaced bodies capable of submersion is a tested technology. For example, the United States Navy constructed NR-1, a small manned submersible; several decades ago, however, it was originally designed to be towed to the operations site as a submersible. This methodology was developed and deployed on USS Batfish. The towing was later converted to use by the Navy, which utilized surface ships to tow the NR-1. The NR-1 has operated for several decades as a submersible towed body. Once released and submerged it operates independently as a manned submersible. The NR-1 is designed as a manned submersible with a crew to operate the small nuclear reactor the submarine systems. Due to it's limited speed it is towed to it's operations site and then released to conduct manned missions. Using NR-1 to approximate a towed body size that has actually been operated as a towed body provides credibility for the towed body concept. The remote operation of submerged bodies in now perfected in the Navy's Unmanned Undersea Vehicles program

(UUV). These technologies are applicable to several mission areas such as remote mine hunting, remote survey and environmental data collection.

12. The number of submersibles needed for carrying out the claimed invention may be readily ascertained by one skilled in the art by determining the gas volume storage capability of each submersible and by using the equations disclosed in the specification for calculating the upwelling volume of gas and the examples of the amount of gas required to produce such as upwelling.

13. For example, a Typhoon hull is approximately 172 meters long with a beam of 23.3 meters which equates to a volume of approximately 73,000 cubic meters. The Trident hull is about 171 meters in length with a 12.8 meter beam and which equates to a volume of approximately 22,000 cubic meters. The near term volume would be to convert the missile tube volume to a gas carrying capacity. The conversion of the tube sizes is described in the table below (numbered references are attached as Exhibit C).

	U.S. Trident Submarine	Russian Typhoon Class
Speed	20+ knots[1]	25+ knots[2]
Depth	300+ m[1]	400+ m[3]
Armament	24 tubes for *Trident* I and II	20 tubes for RSM-52 ballistic missile
Volume	Trident 1 is 34' in length and 74 inches in diameter.[4] The volume per tube is estimated at 1002 ft^3, thus the total volume is 24,048 ft^3.	The RSM-52 is 52.5' in length and 7.83' in diameter.[5] The volume per tube is estimated at 804 ft^3, thus the total volume is 16,000 ft^3.

14. Accordingly, the number of submersibles needed, such as the Typhoon hull having a gas volume capacity of 73,000 m^3, to carrying out the invention would be simply determined by dividing the quantity of liquid gas required for upwelling as described in the application divided by the gas carrying capacity of the submersible. For example, for a volume of 687 million Nm^3 of CO_2, it is estimated that 476 normal cubic meters of gas would be liberated per cubic meter of liquid. Thus, 1.4 million m^3 liquid CO_2 would be required. Accordingly, in the 500-600 m depths where the submersible payloads would be charged with CO_2, only 19 Typhoon hulls would be required.

15. All statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further, that the statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code, and such willful false statements may jeopardize the validity of the application or any patents issuing thereon.

Captain Neil E. Rondorf, USN (Retired)

Date 10-24-07

Exhibit A

Captain Neil E. Rondorf, USN

Commander, Undersea Surveillance

Captain Rondorf was born in Thief River Falls, Minnesota, and graduated from Lincoln High School in 1970. He graduated from the United States Naval Academy with honors in 1974. Following graduation he completed Nuclear Power Training and Submarine School.

From 1975 until 1979, Captain Rondorf served as division officer on board USS ANDREW JACKSON (SSBN 619), participating in six strategic deterrent patrols. He was subsequently assigned as the commissioning crew Weapons Officer on USS INDIANAPOLIS (SSN 697). Upon completion of shakedown and certification, he was ordered to USS ROBERT E. LEE (SSBN 601) as Engineer Officer and completed the last Polaris missile patrol in the Pacific Theater. While serving as Navigator on board USS OMAHA (SSN 692) from 1981 to 1984, the ship completed two deployments to the Western Pacific and the initial 688 class submarine shock trials.

After serving as the Director, Enlisted Academics at the Naval Nuclear Power School from 1984 to 1986, Captain Rondorf was assigned as Executive Officer USS JACKSONVILLE (SSN 699). From 1987 to 1989 the ship completed two deployments, the first full-scale submarine shock trials in twenty years and commenced overhaul. In April 1990 he took command of USS MINNEAPOLIS-ST PAUL (SSN 708) and deployed to the Mediterranean Sea as the first submarine carrying Tomahawk missiles for use in Operation Desert Shield/Storm. The ship was awarded the Meritorious Unit Commendation for its contributions to the conflict.

From November 1992 to July 1994 Captain Rondorf was assigned as Deputy Commander, Submarine Squadron Three in San Diego. From April to July 1993 he commanded USS GURNARD (SSN 662), which was deployed to the Western Pacific. During his tour, Submarine Squadron Three was awarded the Meritorious Unit Commendation for developing submarine joint warfare concepts. From July 1994 to July 1996, he served in the Defense Liaison Division, Office of the Chief of Naval Operations, Washington, DC. In July 1996 Captain Rondorf became the Head, Undersea Surveillance (N874), Submarine Warfare Division on the staff of the Chief of Naval Operations.

Captain Rondorf assumed command of Commander, Undersea Surveillance on 12 August 1999 and retired from active duty on 01 October 2001.

Captain Rondorf is married to the former Cheryl Anne Kruse of Sparta, New Jersey. They presently reside in Virginia Beach, with their three children Ryan, Kira and Kevin. Their son Sean is a Combat Engineer with the 82nd Airborne at Ft Bragg.

Neil E. Rondorf, Science Applications International Corporation, Resume (3/06/06)
Assistant Vice President, Maritime

Education: Bachelor of Science, Oceanography, U.S. Naval Academy. 1974
Master's Equivalent, Nuclear Engineering, Naval Nuclear Power Program, 1976
Master's Equivalent, International Relations, Naval War College, Newport, RI, 1997

Security Clearance: Top Secret

Project lead, Maritime Renewable Technologies development, NAMS Business Unit.

Work Summary: Assistant Vice President, Maritime Operation for 18 months. Five years of technical consulting in maritime industry on commercial and government projects as a member of the SAIC Team. Over 25 years of management and technical engineering of Navy programs including shipboard operations and Integrated Undersea Surveillance System (IUSS) programs. Three years of management in IUSS programs including budgeting, and developing implementation of advanced technology insertions and innovating new concepts utilizing legacy technologies. Two years of operational management including definition of C4ISR/IT needs for the future, sensor design and data processing requirements for IUSS systems including SURTASS/ ADS and Fixed Surveillance programs.

Professional Experience:
Sep 05 – Present: Division Manager, Maritime Engineering
Aug 04 – Sep 05: Maritime Operations Manager, Naval and Maritime Solutions Group.
Nov 2001-Aug 04: Director, Maritime Technologies, SAIC/Technology Research Group: Providing program management assistance to IUSS programs. Program development for Maritime Harbor Security. Concept development for testing emerging technologies at sea. Leading role in building public private partnerships with Virginia Universities to enhance research capability in the state of Virginia
Aug 1999 – Oct 2001: Captain, USN, Commander Undersea Surveillance: Managed budgets and schedules of 8 ships at sea and 3 shore facilities conducting acoustic monitoring and ocean surveillance. Directed effort to define operational requirements for ADS acquisition and develop new processing implementation on both ships and shore facilities. Conducted review of C4ISR/IT program for IUSS requirements and the future programs.
July 1996-July 1999: Captain, USN, Head Integrated Undersea Surveillance Branch-Submarine Directorate, OPNAV Staff: Supervised financial planning and budget for IUSS programs. Reviewed Analysis of Alternatives for ADS to determine the best technical opportunity for ADS acquisition. Worked with SPAWAR PMW's to develop insertion plan for advanced technologies in sensor processing and C4ISR/IT programs.

Miscellaneous:

Appointed to Public – Private Partnership, Virginia Institute of Marine Science at the College of William and Mary, Gloucester, VA

Founding Industry partner, Virginia Coastal Energy Research Consortium
Executive Committee, International Cable Protection Committee
Director, Ocean Renewable Energy Coalition (OREC)
Member: Naval Submarine League
Member, Marine Technology Society

Customers: PMW-181 SPAWAR / College of William and Mary
PEO-IWS Navsea

References:
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Dr. Peter Mikhalevsky, Manager, Ocean Sciences Operation, 703-676-4784
RADM Jack Dantone, (USN, RET) 757-672-5109
Dr. John Wells, Director, Virginia Institute of Marine Science, 804-684-7103

Exhibit B

SSGN www.sublant.navy.mil/HTML/ssgn.htm

A Transformational Force for the U.S. Navy

Home / Subs & Squadrons / SSGN Conversion

Conversion Update

USS Ohio's return to the Fleet was formally recognized at a ceremony in Bangor, Washington on February 7, 2006

Ohio 726	Florida 728	Michigan 727	Georgia 729
• ERO Started Nov 2002 • Conversion Started Nov 2003 • Returned to Fleet Dec 2005	• ERO Started Aug 2003 • Conversion Started Apr 2004 • Returns to Fleet Apr 2006	• ERO Started Mar 2004 • Conversion Started Jan 2005 • Returns to Fleet Dec 2006	• ERO Started Mar 2005 • Conversion Started Oct 2005 • Returns to Fleet Sep 2007

Even beyond its baseline mission capabilities, SSGN offers significant opportunities to develop and test new weapon delivery systems, sensors, and operational concepts that could further transform naval warfare.

SSGN

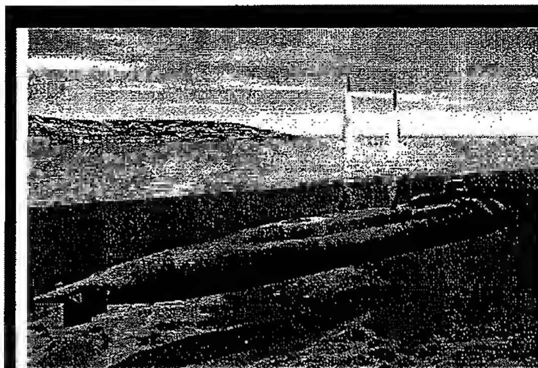
Guided Missile Submarines

Transformation and the Navy

Well before the events of September 11th, the vision of how the military must change to face future threats effectively, and the value of submarines as part of that fight, were clear.

During the Cold War we created the first SSBN by enlarging the partially-constructed hull of the then-named *Scorpion*. In only two years the conversion was complete, the ship was renamed USS *George Washington* (SSBN-598), and the concept of strategic deterrence was changed forever. Clearly, there is a well-established precedent of converting existing platforms into new ones built on proven concepts and the latest technology.

Today's "transformation" efforts include advanced sensors and surveillance systems, rapid precision strike, assured access to hostile or denied areas, and a high "tooth-to-tail ratio" (the ratio of combat power to required support).



SSGN GRAPHIC RESOURCES:

- USS Ohio photos
- SSGN Conversion Update
- TIF image of Ohio Class with ASDS
- Concept drawing of SSGN
- SSGN Cutaway graphic
- Navy Fact File page on SSGNs

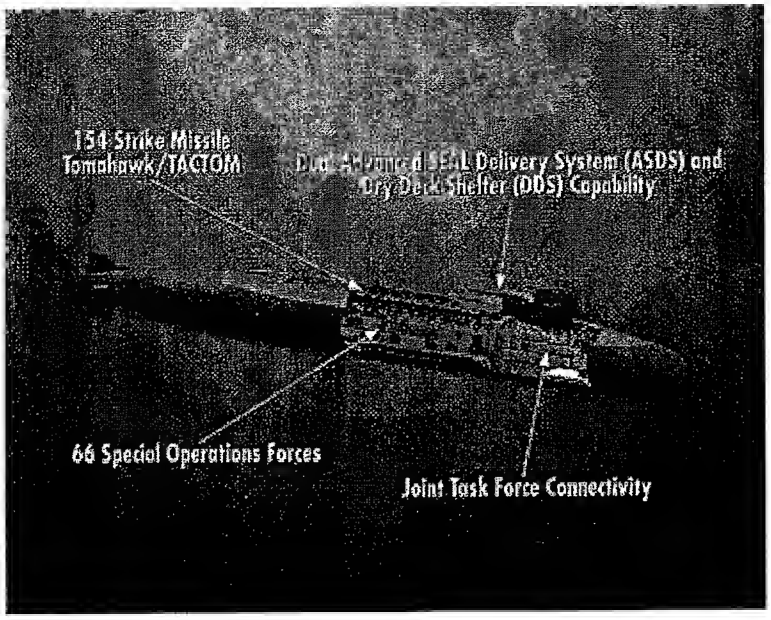
- **Forward Presence** - Utilizing the two-crew concept, the four SSGNs will provide a continuous 2.4 submarines in-theater presence.
- **Strike Capability** - Each of the converted submarines will have the capability to launch up to 154 Tomahawk land attack missiles. The SSGNs have 22 missile tubes, which can house seven missiles per tube in Multiple All-Up-Round Canisters (MACs).
- **Special Operations Capability** – SSGNs will have separate, interchangeable canisters for Special Operations Forces (SOF) equipment that can be installed in place of the MACs. Clandestine insertion and retrieval of SOF operators (via lockout chambers) will be enhanced by the ability of the SSGN to host dual dry deck shelters with SEAL Delivery Vehicles (SDVs) and/or Advanced SEAL Delivery System (ASDS).
- **Connectivity** - SSGNs will be configured for high data rate connectivity using sail-mounted Universal Modular Masts and the Common Submarine Radio Room (CSRR). The Battle Management Center will also provide the SSGN with the capability to host an embarked joint command element.

Responsive, forward-deployed units, survivable against anti-access threats, and capable of sustained high-volume strike with minimal logistic support, score high in these categories - SSGN is a prime example.

Overview of SSGN Capabilities

Here is a quick summary of the capabilities SSGN brings to Joint Warfare:

- TRIDENT stealth and reliability, with more than 20 years of service life remaining for each



SSGN

- Large-volume precision strike, with up to 154 Tomahawk and Tactical Tomahawk cruise missiles

- Sustained Special Forces operations to include insertion, extraction, and support of 102 Special Forces personnel, conditioned and ready, with onboard periods much longer than on SSNs

- Command center for mission planning and execution

- Capacity for conducting other SSN missions, such as: intelligence, surveillance, reconnaissance, and targeting; anti-submarine warfare; anti-surface warfare; and mine warfare

- High-data-rate connectivity and joint command/control capability with a "*Virginia*-class" advanced SSN radio room and ISR suite

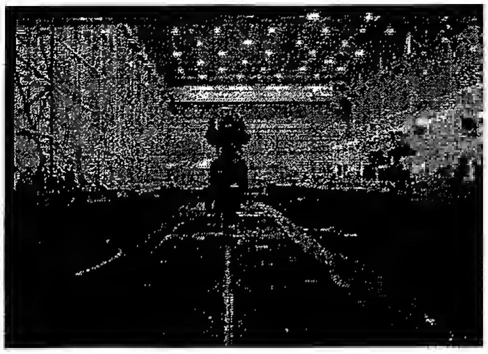
- 67 percent operational availability by using two crews to achieve a continuous, 2.4-ship deployed presence in support of Combatant Commanders' mission requirements

- 20 times the payload of an SSN, with large ocean interfaces (22 seven-foot diameter launching tubes, two for SOF lock-out), opportunity for payload experimentation and development

Payload

Stealth, endurance, and agility have long enabled nuclear-powered submarines to take sensors and precision weapons into the fray with little or no logistical support. However, in spite of their unmatched supremacy beneath the world's oceans and their ability to strike with impunity with dozens of cruise missiles, the greatest limitation of today's attack submarines is payload.

Even beyond its baseline mission capabilities, SSGN offers significant opportunities to develop and test new weapon delivery systems, sensors, and operational concepts that could further transform naval warfare. Two examples already envisioned are encapsulated launch of a variety of tactical munitions and deployment of large unmanned undersea vehicles (UUVs) and off-board sensors. Encapsulated launch will send weapons to the surface for dry-launching, using a standardized buoyant capsule and a common interface for loading and communications. This modular approach to payloads will even allow use of "off-the-shelf" weapons, unmanned aerial vehicles, and decoys in support of joint forces. And, by developing large UUVs that make full use of the seven-foot tubes, they can surpass the range, endurance, and payload of small surveillance platforms and take on new missions - even offensive ones.



Strike Capabilities

The SSGN will bring a new dimension to strike warfare. Currently, SSNs with up to two-dozen Tomahawks usually launch missiles in salvos of three or four (16 maximum), while on SSGN a salvo of 32 missiles will represent less than 15 percent of the full load of 154 missiles. Existing submarine torpedo-tube launched (TTL) TLAMs will be converted for vertical launch to provide the required load-outs. Obviously, the number of TLAMs available to deploying SSNs will decrease as a result, but if you consider that a missile on an SSGN is deployed 70 percent of the time, the overall TLAM inventory immediately available to the Combatant Commanders will increase by about 50 to 60 percent. This shift of weapons will also open up some room in SSN torpedo rooms for more torpedoes or alternative payloads, like LMRS and other unmanned vehicles.

Special Operations Forces (SOF)

SEALs have operated from submarines for years. Conversion of the SSBNs USS *James K. Polk* (SSN-645) and USS *Kamehameha* (SSN-642) - since inactivated - gave us the space for embarked SEALs to work out and maintain their conditioning for extended periods and to deploy with their equipment. SSGN will not only restore the force's large, sustainable SOF capability, but will include significant command and control capabilities well beyond those of previous boats. With a dedicated command center and a "*Virginia*-class" communication system, SSGN will be able to control a Special Forces campaign over a period of months from her covert position. Once on scene, SSGN will deploy Special Forces submerged, either from the SEAL delivery vehicles (SDVs) housed in the dry-deck shelters, or in the Advanced SEAL Delivery System (ASDS) underwater vehicle, which transports SEALs inside a dry environment. SSGNs should prove to be the most advanced covert Special Forces platforms ever.

Mission Agility

The SSGN's inherent stealth and endurance - as with all nuclear-powered submarines - will enable it to conduct many traditional SSN surveillance or sea control missions, even though it will be optimized for strike and Special Operations Forces because of its immense payload capacity. The SSGN can conduct a wide range of missions in a single deployment. SSGN is a highly flexible multi-mission platform capable of supporting the following operational objectives:

- Assure access to the contested littorals
- Acquire actionable intelligence
- Dissuade and deter by holding vast target sets at risk
- Strike with precision and surprise in support of the JFC's objectives

The mission agility of our nuclear-powered submarines and their broadly trained crews makes them capable of nearly any submarine mission.

Concept of Operations

Dual-crewed SSGNs will deliver these extraordinary warfighting capabilities with unrivaled efficiency. SSGNs will have a deployment cycle similar to TRIDENT SSBNs, with every other crew turnover at a forward-deployed site to achieve a higher operational availability and in-theater presence. A strong, efficient, and well-established infrastructure is required to make this work, and we already have that in

the TRIDENT program. Since the TRIDENT maintenance and support systems are located in Bangor, Washington, and Kings Bay, Georgia, it follows that the most cost-effective option for homeporting SSGN will be at those bases. With four SSGN conversions, two will be stationed on each coast to balance support to the EUCOM, CENTCOM and PACOM theaters. Locations for the forward-deployed turnovers will depend on where they are operating.

SSGNs will be accountable under current START counting rules, and it is important that SSGN be part of future arms control agreements.

Since 1960, SSBNs have guaranteed our security by deterring the use of weapons of mass destruction against the United States. In keeping with the objectives of a transformed Navy, we now have the opportunity to re-deploy these successful ships to make use of their incredible payload, stealth, and endurance in a new deterrent role. With future enemies certain of both our capability and determination - but *un*certain about when and from where our new SSGNs might attack, we achieve a powerful, new level of deterrence and open a door to new capabilities and operational concepts yet to be imagined for submerged, survivable platforms..

Exhibit C

<u>References</u>

1. http://www.navy.mil/navydata/fact_display.asp?cid=4100&tid=200&ct=4

2. http://www.naval-technology.com/projects/typhoon/

3. http://www.fas.org/nuke/guide/usa/slbm/ssbn-726.htm

4. http://www.fas.org/nuke/guide/usa/slbm/c-4.htm

5. http://www.navweaps.com/Weapons/WMRUS_RSM-52.htm

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re application of: Ronald D. BLUM, ET AL.	Confirmation No. 9812
Application No.: 09/994,860	Examiner: Boeckmann, Jason
	Technology Center/Art Unit: 3752
Filed: November 28, 2001	
For: METHOD AND APPARATUS FOR REDUCING THE INTENSITY OF HURRICANES AT SEA BY DEEP-WATER UPWELLING	
Customer No.: 20350	

Mail Stop AF
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

DECLARATION UNDER 37 C.F.R. § 1.132

I, Vickie Lien Singleton, declare the following:

1. I hold a Bachelor of Science degree in Mechanical Engineering from West Virginia University, a Master of Science in Civil Engineering, specializing in airlift aerator modelling, from Virginia Polytechnic Institute and State University, and am currently a fourth year Ph.D. candidate at Virginia Polytechnic Institute and State University studying bubble plume dynamics and water quality modelling. A copy of my resume is attached as Exhibit A.

2. I have read and am familiar with the above-referenced application. I have also read and am familiar with the Office Action mailed May 4, 2007 ("Office Action") pertaining to this application.

3. I have been retained by the assignee of the above-identified application to assist in responding to the Office Action. I have no financial interest in the assignee or the outcome of this patent application, including whether it issues as a patent or not. I am being compensated for the time spent on this matter at the rate of $200/hr, plus reasonable expenses.

4. It is my understanding that the claims currently under examination, which relate to, inter alia, methodologies for reducing the intensity of a hurricane, were rejected as allegedly being wholly inoperative, lacking credible utility, and not enabled. Specifically, the Examiner asserts:

> ...applicant admits in his arguments, "submersibles of the kind required for this application do not presently exist." It seems that applicant wishes that someone will come along and develop the technology required to make the required submersibles, thereby enabling the present invention. Therefore, it is impossible for one of ordinary skill in the art at his time to make and or use this invention. Office Action at page 6.

5. This Declaration provides support for an initial order-of-magnitude estimate of the gas flow rate and the quantity of gas required to induce an adequate upwelling flow rate to lower the temperature of the upper sea surface, using the amount of direction provided for in the specification in combination with the knowledge of one skilled in the art at the time of filing the application, such as the use of two existing bubble-plume models, without any undue or unreasonable experimentation. In particular, the specification is replete with the detailed description of various gas sources (see, e.g., para 0029), submersible designs (see, e.g., para 0034), inception strategies (see, e.g., 0026-27, 49-64), and the exemplary calculation for upwelling volume required for successful surface layer water cooling (see, e.g., 0049-64).

6. The specification is directed to reducing the intensity of hurricanes at sea by upwelling deep-water in the ocean. To obtain an initial order-of-magnitude estimate of the gas flow rate required to induce an adequate upwelling flow rate, two existing bubble-plume models were

applied. Each model is based on the discrete-bubble method developed by Wüest, A. ET AL., WATER RESOUR. RES. 1992, 28, 3235-3250, and accounts for ambient density stratification and mass transfer between bubbles and water. The circular bubble-plume model was published in 1992 and is for a circular or round gas diffuser. The linear bubble-plume model was first presented in 2001 (McGinnis, D. ET AL., Asian Waterqual 2001: First IWA Asia-Pacific Regional Conference: Fukuoka, Japan, 12-15 Sept. 2001) and was later refined and validated in 2007 (Singleton, V. ET AL., WATER RESOUR. RES. 2007, 43, W02405). This model is for a long and narrow diffuser. Both diffuser configurations were modeled to compare the effects of geometry on upwelled or induced water flow rate. Based on the design example in the patent application, it was assumed that the diffusers would be located at about 300 m depth when bubbling. The patent application states that carbon dioxide is the preferred gas, so model calculations focus on this compound. Because they are used for lake oxygenation studies, the solubility (Weiss, R. ET AL., Mar. Chem. 1974, 2, 203-215) and mass transfer coefficients (Clift, R., ET AL., BUBBLE, DROPS, AND PARTICLES New York, NY, 1978) of the bubble-plume models were modified for carbon dioxide, and the effect of dissolved carbon dioxide on water density was included (Weiss ET AL, *supra*). The Wüest reference is attached as Exhibit B, the McGinnis reference is attached as Exhibit C, the Singleton reference is attached as Exhibit D, the Weiss reference is attached as Exhibit E, and the Clift reference is attached as Exhibit F.

7. To apply the models, boundary condition profiles of temperature and salinity are needed. In an attempt to closely represent the design example of the application, profile data collected off the eastern coast of Florida (26.17N,-78.80W) on September 19, 2007 were used (www.aoml.noaa.gov/phod/trinanes/tmp/dxbt1190840242.dat). The depth of the 26° C isotherm in this recent profile is approximately 81 m, which is slightly more conservative than the 70 m depth of the patent application design example. The models also require the dimensions of the diffusers and the initial bubble size. The initial bubble size was assumed to be 10 mm. As a starting point, the length of the linear diffuser was assumed to be proportional to the length of an SSBN-726 Ohio-Class submarine, which is about 170 m. Using a linear diffuser

length and width of 150 m and 13 m, respectively, produces a diffuser area of 1,950 m^2. An equivalent diameter for the circular diffuser for this cross-sectional area is approximately 50 m.

8. Using these initial and boundary conditions, each model was run over a range of applied gas flow rates (2,000–20,000 Nm^3/s) to a single diffuser system or unit. Because the intent of the apparatus is to cool surface waters, the lowest gas flow rate that upwelled water to and detrained at the surface was selected. The gas flow rates that induced plumes to the surface were 10,500 and 12,500 Nm^3/s for the linear and circular diffusers, respectively. The depth of the 26°C isotherm, the temperature below which hurricane development is hampered, was 81 m. Therefore, only plume induced flow rates from 300 to 81 m depth are considered as effective upwelling flow rates. For the previously stated gas flow rates, the plume water flow rates at the depth of 26°C isotherm are 51,900 and 51,300 m^3/s for a single linear and circular diffuser, respectively. These flow rates represent the upwelling flow rate from deeper water into the effective epilimnion or surface layer. Even though the plume continues to rise through the epilimnion and entrain ambient water, plume induced flow that occurs within the effective epilimnion does not contribute to the upwelling into this volume. It would be expected that the artificial upwelling of the deep, cold seawater to the sea surface layer by the bubble-driven plume would create an upper ocean layer region of sufficiently lower temperature.

9. Referring to the patent application, the maneuver before upwelling submersible mobilization strategy is estimated to require a total upwelled water flow rate of at least 12.1 million m^3/s. Using the estimated water flow rate values of 51,900 and 51,300 m^3/s for a single linear and circular diffuser unit, respectively, a total of 233 linear or 236 circular diffusers may be needed. This corresponds to total gas flow rates of 2.45 and 2.95 million Nm^3/s for the linear and circular diffusers, respectively. Per the patent application, the maneuver before upwelling strategy requires a total gas volume of 5.29×10^{10} Nm^3 for the linear diffusers and 6.37×10^{10} Nm^3 for the circular diffusers. Assuming that 476 Nm^3 of gas would be liberated per cubic meter of liquid, the amount of liquid CO_2 required for linear diffusers would be about 1×10^8 m^3 and about 1.3×10^8 m^3 for circular diffusers.

10. All statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further, that the statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code, and such willful false statements may jeopardize the validity of the application or any patents issuing thereon.

Vickie Lien Singleton

Date 11-1-07

Exhibit A

10. Education and Experience:

January 2003 to Present

- Enrolled in Ph.D. program at Virginia Polytechnic Institute and State University
- Current GPA: 4.0

June 2000 to January 2003

- Employed as Design Engineer at Black & Veatch Corporation, Louisville, KY
- Responsible for coordination of air permitting requirements for a $70 million design-build project for wastewater solids processing. Coordinated training for plant staff. Performed field review for development of as-built drawings.
- Detailed design of influent pumping station and associated yard work. Coordinated design support groups. Developed hydraulic profile of new and future treatment facilities. Responsible for obtaining required permits and approvals.
- Assisted with determination of future treatment costs for a 20-year facility plan for a 130-mgd water utility. Reviewed client's specifications for distribution system projects. Determined storage and feed capacity of chemical equipment.
- Drafted preliminary engineering report for $15 million water distribution system expansion. Researched permits required for construction of project.

May 1998 to June 2000

- Employed as Staff Engineer at Black & Veatch Corporation, Greenville, SC
- Responsible for shop-drawing review and maintenance of construction correspondence databases for a $25 million wastewater plant expansion to 7.5 mgd.
- Preparation of scope of work, specifications, and cost estimate to provide assistance to achieve improved NPDES permit compliance for in-plant sewer overflows.
- Served as project engineer for comprehensive facility plan of a 60-mgd plant that evaluated unit process operation and expansion to 90 mgd. Responsible for hydraulic evaluation of plant, drafting of technical memoranda, and coordination of personnel.

August 1995 to May 1998

- Attended Virginia Polytechnic Institute and State University
- Received M.S. in Environmental Engineering
- Final GPA: 4.0 (Summa Cum Laude)

August 1991 to May 1995

- Attended West Virginia University
- Received B.S. in Mechanical Engineering
- Final GPA: 3.6 (Magna Cum Laude)

11. Publications: [including under maiden name of Vickie Lien Burris]

Burris, V. L. and Little, J. C. (1998). Bubble dynamics and oxygen transfer in a hypolimnetic aerator, *Water Science & Technology*, **37** (2) 293-300.

Burris, V. L., McGinnis, D. F. and Little, J. C. (2002). Predicting oxygen transfer and water flow rate in airlift aerators. *Water Res*earch, **36**, 4605-4615.

Singleton, V.L. and Little, J.C. (2006). Designing hypolimnetic aeration and oxygenation systems – A review, *Environmental Science and Technology*, **40**, 7512-7520.
Singleton, V.L., Gantzer, P. and Little, J.C. (2007). Linear bubble plume model for hypolimnetic oxygenation – Full-scale validation and sensitivity analysis, *Water Resources Research*, **43**, W02405.

12. Other projects

December 2004 to January 2005

- Drafted responses to Virginia Department of Environmental Quality questions regarding dissolved oxygen criteria for lakes and reservoirs

March to May 2005

- Lake oxygenation modeling expert for oxygenation pre-pilot design investigation for Onondaga Lake, NY

July 2005

- Co-author author for technical report "Development of Building Blocks to Prescribe Ecological Flows for the Rivanna River Watershed"

December 2006

- Second author for technical report "Review of Oxygenation Technologies with Special Reference to Application in the Upper Swan Estuary"

February 2004 to present

- Critical peer review of nine manuscripts submitted by other researchers for journal publication

Exhibit B

WATER RESOURCES RESEARCH, VOL. 28, NO. 12, PAGES 3235–3250, DECEMBER 1992

Bubble Plume Modeling for Lake Restoration

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W. M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology, Pasadena

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Environmental Physics, Institute for Aquatic Sciences and Water Pollution Control
Eidgenössische Technische Hochschule, Zurich, Switzerland

A steady bubble plume model is developed to describe a weak air (or oxygen) bubble injection system used for the restoration of deep stratified lakes. Since the model is designed for two modes of operation, i.e., oxygenation and artificial mixing, gas exchange between water and bubbles has to be included. The integral model is based on the entrainment hypothesis and a variable buoyancy flux determined by the local plume properties and the ambient water column. Fluxes of eight properties are described by nonlinear differential equations which can be numerically integrated. In addition, five equations of state are used. The model leaves open two initial conditions, plume radius and plume velocity. Model calculations with real lake water profiles demonstrate the range of applicability for both modes of operation. The model agrees reasonably well with field data and with laboratory experiments conducted by various investigators.

1. INTRODUCTION

In spite of enormous efforts made to fight lake eutrophication, in many lakes concentrations of phosphorus and other planktonic nutrients are still far above critical values [*Rast and Lee*, 1983]. As a consequence of high primary productivity values, oxygen concentrations in the hypolimnion of eutrophic lakes drop to low values or even to zero. So-called internal lake restoration measures have been designed to improve the hypolimnic oxygen levels and to limit the recycling of phosphorus from the sediments into the lake water [*Imboden*, 1985]. Two restoration techniques which can be used separately or in combination are (1) artificial mixing of the water column during the cold season and (2) input of oxygen into the hypolimnion during summer in such a way as to preserve the stratification.

Artificial mixing is technically simpler and also cheaper and is thus usually the first method to be evaluated. It is designed to add extra mixing energy to the lake at the time when the density stratification is weakest in order to allow water exchange down to the very bottom, or, if mixing occurs naturally, to prolong the period of mixing. Complete mixing maximizes the uptake of oxygen by natural gas exchange at the water surface. In fact, incomplete mixing may not only result from low wind exposure but may also be a consequence of lake eutrophication: Mineralization of biomass in the hypolimnion often leads to the steady accumulation of dissolved substances in the deep waters and thus to a chemically induced permanent stratification [*Joller*, 1985]. In some lakes, the hypolimnic oxygen reserves may not be large enough to prevent the hypolimnion from becoming anoxic during the summer, even if complete saturation had been achieved during the winter. In such situations, oxygen can be artificially introduced into the hypolimnion during the summer. This is commonly combined with artificial mixing during the winter.

Artificial mixing is achieved, in most cases, by injecting compressed air into the deepest part of the lake. However, different technical systems have been designed for the injection of oxygen into a stratified lake. One frequently used system is the Atlas-Copco "Limno" device [*Bucksteeg and Hollfelder*, 1978]. This system consists of two concentric tubes placed vertically in the water column. Air is pumped into the lower end of the inner tube, in which the water rises, then sinks back through the outer tube and leaves the system through outlets placed at the appropriate depth.

In this article a different approach is described. The system "Tanytarsus," designed by the two Swiss engineers, E. Jungo and U. Schaffner, is presently in operation in several deep Swiss lakes [*Imboden*, 1985; *Stadelmann*, 1988; *Stöckli and Schmid*, 1987]. The system uses the same lake installation for both the injection of compressed air for artificial mixing in winter and the injection of pure oxygen into the hypolimnion in summer (Figures 1*a* and 1*b*). Pure oxygen is used for hypolimnic oxygenation to prevent the accumulation of molecular nitrogen which can be toxic to fish [*Fast and Hulquist*, 1982].

Both modes of operation are physically similar. The main difference between them consists in the choice of the initial bubble radius and the selection of either natural air or pure oxygen. During the winter the air bubbles have to be large enough to guarantee that the buoyancy force acts up to the lake surface. In contrast, for efficient oxygenation, the oxygen bubbles have to be small enough to dissolve completely in the oxygen-poor hypolimnion before entering the

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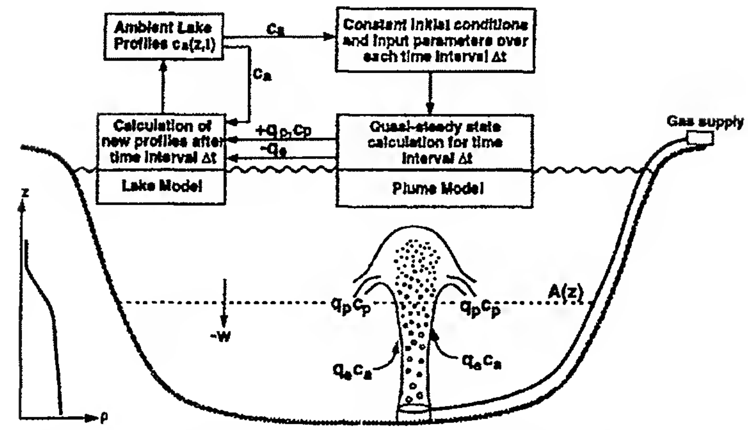

Fig. 1*a*. Schematic diagrams of the application of the bubble injection system (below) and of the coupling of the plume model with a water quality lake model (above). The two models should run independently of one another, alternating over a short time interval (steady input) to supply one another with their respective required input variables. Labeled quantities are those appearing in (24) and (25).

oxygen-rich surface waters. In addition, the bubble plume should be weak enough so that the induced water circulation is restricted to the hypolimnion. Otherwise, the induced flux of nutrients from the hypolimnion into the epilimnion could further stimulate primary production in the lake.

Diffusors for both modes of operation have been successfully designed and employed in several medium-sized Swiss lakes (Baldeggersee, Sempachersee, Hallwilersee). In order to optimize design and operation of the installations with respect to oxygen input and energy consumption it is important to gain a better understanding of the behavior of the bubble plume in a stratified environment. In this article, classical plume theory is extended to include gas-water exchange of oxygen and nitrogen as well as bubble expansion due to decreasing pressure during bubble rise. The mathematical plume model is presented in sections 2.1–2.6; then the relationship of the plume model to an overall lake model is discussed briefly in section 2.7. In section 3 the model is applied to the two standard cases of operation, oxygenation and artificial mixing, respectively, and compared with a field experiment. Results and questions remaining open are discussed in section 4, and conclusions are given in section 5.

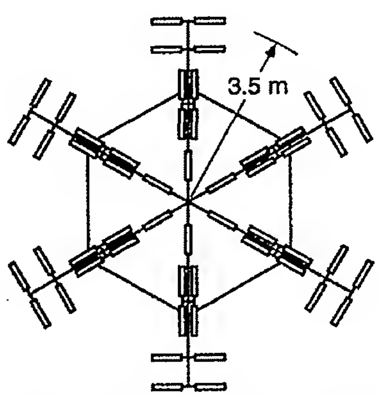

Fig. 1*b*. Top view of one diffusor unit, consisting of 54 tubes (courtesy of Ingenierbüro Jungo, Zürich, Switzerland).

2. DEVELOPMENT OF THE BUBBLE PLUME MODEL IN STRATIFIED WATER

2.1. *Previous Work*

Air bubble plumes, induced by the steady release of air into water, have been widely studied both experimentally and theoretically. Previous work, which has been mainly concentrated on plumes in homogeneous water, has revealed various characteristics of the flow: the Gaussian radial distribution of plume velocity and bubbles, the similarity of the radial profiles at different distances from the source, and the entrainment of the surrounding water. Measurements have been carried out over a wide range of water depths from centimeters [*Durst et al.*, 1986] to meters [*Kobus*, 1973; *Ditmars and Cederwall*, 1974; *Goossens*, 1979; *Fannelop and Sjoen*, 1980; *Milgram and Van Houten*, 1982] and up to tens of meters [*Topham*, 1975; *Milgram*, 1983] with airflow rates from 4×10^{-7} N m^3 s^{-1} (weak plume [*Leitch and Baines*, 1989]) to 0.66 N m^3 s^{-1} (strong plume [*Topham*, 1975]).

Theoretical investigations followed the early work of *Ditmars and Cederwall* [1974], who applied the integral theory of a single-phase plume [*Morton et al.*, 1956] to the two-phase bubble plume. The theory is based on the horizontally integrated equations of conservation of mass, momentum and buoyancy and on the entrainment hypothesis, which states that the volume of entrained water per unit height is proportional to both the local plume velocity and the plume circumference. Compressibility of the air and bubble slipping, i.e., the differential velocity between rising bubbles and the plume water, are two features which are usually also included in bubble plume models. The effect of turbulent transport within the plume was taken into account by *Milgram* [1983] who introduced the momentum amplification factor γ (ratio of total momentum flux to the momentum flux carried by the mean flow).

Far less work has been done on stratified water bodies.

McDougall [1978] generalized the integral model for a stratified ambient fluid. Experiments, carried out in strongly stratified [*McDougall*, 1978] and weakly stratified [*Hussian and Narang*, 1983] water revealed a double plume structure in which the bubbles remain in the center part, whereas the pure liquid outer part of the plume can spread out at certain levels.

If bubble plumes are applied to destratify lakes and reservoirs it is important to optimize the airflow rates required to overcome a given stratification. A concept of maximum efficiency was demonstrated experimentally for linear stratification by *Asaeda and Imberger* [1988]. *Patterson and Imberger* [1989] combined *McDougall*'s [1978] bubble plume model with the one-dimensional dynamic lake model DYRESM to evaluate destratification in response to air bubble plumes and weather. With a similar goal in mind, *Zic and Stefan* [1990] have even developed models to simulate the entire flow field induced by a bubble plume in a lake.

In this section, the integral plume theory will be extended to include not only bubble expansion [*Ditmars and Cederwall*, 1974], but also gas exchange (dissolution and stripping) for the dynamics of a buoyant plume. Previous investigators have not included the latter feature, which is important in deep lakes and for weak plumes. The bubble model will also include the effects of density stratification due to gradients of both vertical temperature and dissolved solids. The model can cope with arbitrary ambient profiles of dissolved oxygen and nitrogen.

2.2. *Model Features and Assumptions*

Previous investigators have presented the basic equations for bubble plumes, and discussed the problem of estimating suitable parameters such as the entrainment coefficient, α, and the spreading ratio of bubbles to fluid flow, λ. The new features of the proposed model for lake use are (1) finite source diameter; (2) induced vertical water velocity at the level of the diffusor as an initial condition; (3) exchange of gases (oxygen and nitrogen primarily) between bubbles and liquid in the plume; (4) conservation equations for specific gases in both dissolved and gas phases; (5) variable gas composition of bubbles during rise; and (6) arbitrary ambient profiles for temperature, salinity (mass of dissolved solids per mass of solution), and dissolved oxygen and nitrogen. Other features included in the plume model are variable bubble radius due to expansion and dissolution; bubble slip velocity and gas mass transfer coefficient as a function of bubble radius, and solubility constants for oxygen and nitrogen as a function of temperature.

The principal assumptions used in developing the model for a steady rising bubble plume in uniform or stratified environment are as follows:

1. The variation of the effective mass density, $\Delta\rho$, is important only in the gravity terms and not for mass or momentum fluxes (Boussinesq assumption, as in all plume theories). This is also equivalent to assuming relative gas volume concentration $V_g \ll 1$.

2. The mass density of gas is neglected compared to that of water in the momentum equation.

3. Uniform distributions ("top hat") across the plume are assumed for water velocity, temperature, dissolved solids, dissolved gases and bubble velocity and concentration (as well as for individual gases) (Figure 2). This is simpler than trying to use Gaussian profiles, and will yield all the correct scaling relationships; also for large sources whose size is a significant fraction of the depth, we avoid the need for special treatment of a zone of flow establishment, during which top hat profiles at the source would have to change to Gaussian profiles. *Morton* [1959] and *Fannelop and Sjoen* [1980] have shown that the top hat distribution captures the main flow features, and that only the constants need to be adjusted.

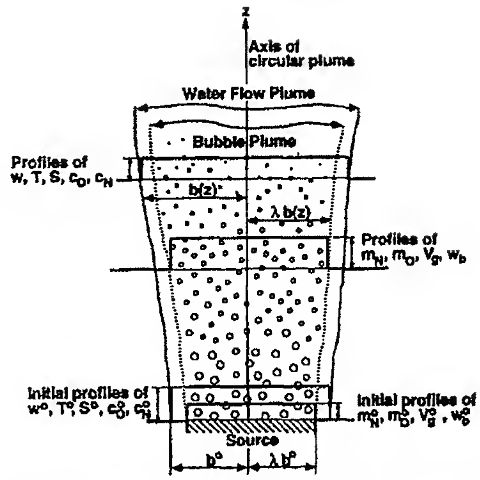

Fig. 2. Diagram defining the bubble plume geometry, showing circular "top hat" distributions. The top hat radius of the bubble core, λb, is smaller than the plume radius b. The latter is assumed to apply for all properties of dissolved species, including temperature (T) and plume velocity (w). Variables are defined in Tables 1, 3*a* and 3*b*.

4. The plume radius b for dissolved species (dissolved solids and dissolved nitrogen and oxygen) and temperature is assumed to be equal to the radius of the top hat plume velocity, whereas that for the bubbles is only λb, where $\lambda \leq 1$. (Although it is expected that dissolved substances will actually spread slightly faster than momentum, such a distinction is an unnecessary complication in this case where the bubbles are the major source of buoyancy.)

5. Ambient currents (other than the plume entrainment velocity) are assumed to be zero.

6. The plume is fully turbulent.

7. The turbulent transport of momentum and scalar quantities (heat, salinity, gases) is neglected compared to advective transport calculated from the mean flow. This is equivalent to taking *Milgram*'s [1983] momentum amplification factor equal to 1.0, which appears reasonable from his experiments.

8. The bubble source is assumed to produce bubbles at a constant rate uniformly distributed over the circular source area of radius λb^o.

9. Bubble coalescence is neglected, or else the rate of change of the number of bubbles is prespecified. In this model, the number flux of bubbles, N, is kept constant with height and equal to the number flux at the source.

10. The bubbles are all of uniform size (or are adequately represented by a suspension of equal bubbles). If instead a bubble size spectrum were prespecified, it would be possible

TABLE 1. List of the Eight Basic Plume Variables

Variable	Symbol	Units
Vertical velocity of the plume water	w	$m\ s^{-1}$
Plume radius for velocity and dissolved species	b	m
Temperature of plume water and bubbles	T	°C
Total dissolved solids in plume water*	$S\rho_w$	$kg\ m^{-3}$
Concentration of dissolved O_2	c_O	$mol\ m^{-3}$
Concentration of dissolved N_2	c_N	$mol\ m^{-3}$
Concentration of gaseous O_2†	m_O	$mol\ m^{-3}$
Concentration of gaseous N_2†	m_N	$mol\ m^{-3}$

Variables with index a, i.e., T_a, S_a, c_{Oa}, c_{Na}, describe "ambient" (i.e., lake water) properties.
*S denotes salinity (mass of salt per mass of solution).
†Amount of gas per unit bulk volume of the bubble-water mixture within the bubble plume of radius λb.

to replace the number flux of bubbles N by an array $N(r_1, \cdots, r_n)$ and to calculate the fate of the individually sized bubbles independently.

11. Water properties of the initial plume are those of lake water at that depth (where the diffusor is installed).

12. Gas exchange between water and bubbles for gases other than oxygen and nitrogen (e.g., argon, carbon dioxide, methane) is neglected. However, other gases could easily be included in the model by adding the relevant conservation equations.

2.3. *Conservation Equations*

There are eight basic plume variables (Table 1) to be calculated by simultaneous integration of eight differential equations describing the plume dynamics based on the conservation laws for mass, momentum, and heat (Table 2). Several additional parameters are introduced into the model which can be calculated either from the corresponding equations of state (Table 3*a*) or from empirical approximations taken from the literature (Table 3*b*). In the following the reader is referred to Tables 1–3 for the definition of variables and parameters.

Continuity for plume water flow. The rate of change of the volume flow is given by the entrainment of ambient water into the plume:

$$\frac{d}{dz}[\pi b^2 w(1-\lambda^2 V_g)] = 2\alpha\pi b w \quad (m^2\ s^{-1}) \qquad (1)$$

where z is the vertical coordinate (positive upward) and α, the entrainment coefficient for the top hat plume, is $\sqrt{2}$ times the corresponding value used for a Gaussian plume model, α_g, i.e.,

$$\alpha = \sqrt{2}\,\alpha_g \quad \text{(dimensionless)} \qquad (2)$$

as explained by *Morton* [1959]. Furthermore, the top hat radius is

$$b = \sqrt{2}\, b_g \quad (m) \qquad (3)$$

where b_g is the plume width in the Gaussian model ($w = w_m \exp(-r^2/b_g^2)$). The term $\lambda^2 V_g$ is a correction for the volume occupied by the gas bubbles. Since $V_g < 10^{-2}$ for bubble plumes of interest for lake restoration, and following the Boussinesq assumption, we may rewrite the equation without the V_g term:

$$\frac{d}{dz}(\pi b^2 w) = 2\alpha\pi b w \quad (m^2\ s^{-1}) \qquad (4)$$

Momentum flux. We may again neglect the gas volume and gas momentum in calculating the momentum flux $M = \pi b^2 w^2$ of the plume. The rate of change of M with height z is equal to the buoyant force per unit height of the plume:

$$\frac{d}{dz}(\pi b^2 w^2) = \frac{\rho_a - \rho_p}{\rho_p} g\pi b^2\lambda^2 + \frac{\rho_a - \rho_w}{\rho_p} g\pi b^2(1-\lambda^2) \quad (m^3\ s^{-2}) \qquad (5)$$

(ρ_a and ρ_w are densities of ambient and plume water, respectively, and ρ_p is the density of the plume bubble-water mixture). On the right-hand side the first term gives the buoyant force for the area of the bubble distribution top hat, $\pi\lambda^2 b^2$. The second term is the (negative) buoyancy for the fluid inside the annulus (Figure 2) between the bubble top hat (radius λb) and the plume velocity top hat (radius b). When there is no ambient fluid stratification ($\rho_a = \rho_w$) or when $\lambda \approx 1$, the second term vanishes.

Heat or temperature flux. Assuming that the coefficient

TABLE 2. Definition of the Eight Integrated Flux Variables

Variable	Formula	Units
Volume flux of plume water	$\mu = \pi b^2 w$	$m^3\ s^{-1}$
Momentum flux	$M = \pi b^2 w^2$	$m^4\ s^{-2}$
Temperature flux (relative to T = 0°C)	$F_T = \mu T$	$°C\ m^3\ s^{-1}$
Flux of total dissolved solids	$F_S = \mu S\rho_w$	$kg\ s^{-1}$
Flux of dissolved O_2, N_2	$D_i = \mu c_i$; i = O, N	$mol\ s^{-1}$
Flux of gaseous O_2, N_2	$G_i = \pi b^2\lambda^2(w + w_b)\, m_i$, i = O, N	$mol\ s^{-1}$

TABLE 3*a*. Equations of State

Parameter	Equation	Comments
Partial pressures within bubble at depth z	$p_i = [m_i/(m_O + m_N)]p = [G_i/(G_O + G_N)]p$ for i = O, N (bar)	Total pressure p is given by the hydrostatic approximation
Total pressure	$p = p_s + a \int_z^{z_s} \rho_a g \, dz = p_s + a \bar{\rho}_a g(z_s - z)$ (bar)	p_s is atmospheric pressure at lake surface (bar); z is vertical distance above diffusor (m); z_s is height of lake surface above diffusor (m); g is acceleration of gravity, equal to 9.81 m s^{-2}; $\bar{\rho}_a$ is mean density of ambient water; and a is a pressure conversion factor (pascals to bars), equal to 10^{-5} bar kg^{-1} m s^2.
Water density at atmospheric pressure	$\rho_a = f_T(T_a) + f_s(S_a)$ for ambient lake water, $\rho_w = f_T(T) + f_s(S)$ for plume water	$f_T(T) = 999.868$ kg m^{-3} + 10^{-3} $[a_1 T + a_2 T^2 + a_3 T^3]$; $a_1 = 65.185$ kg m^{-3} $°C^{-1}$; $a_2 = -8.4878$ kg m^{-3} $°C^{-2}$; $a_3 = 0.05607$ kg m^{-3} $°C^{-3}$; $f_s(S) = \gamma S$, where either $\gamma = 0.802$ kg m^{-3} (‰)$^{-1}$ if S is salinity expressed as dissolved salt content in per mil or $\gamma = 0.705 \times 10^{-3}$ kg m^{-3} (µS/cm)$^{-1}$ if S is expressed in terms of the electrical conductivity measured at 20°C (modified after *Bührer and Ambühl* [1975]).
Density of bubble-water mixture in plume	$\rho_p = (1 - V_g)\rho_w$	
Gas volume*		
Ideal gas law	$V_g = [(m_O + m_N)/p]R\hat{T}$	R = 8.314 J mol^{-1} K^{-1} (gas constant) and $\hat{T}$ is absolute temperature of plume water (K)
Van der Waals gas law	Implicit equation for V_g: $[V_g/(m_O + m_N) - b_v] \cdot [p + a_v(m_O + m_N)^2/V_g^2] = R\hat{T}$	$a_v = 1.4 \times 10^{-6}$ bar m^6 mol^{-1}; $b_v = 32 \times 10^{-6}$ m^3 mol^{-1}
Bubble radius	$r = (3V_g \lambda^2 b^2 (w + w_b)/4\pi N)^{1/3}$	N is the number flux of bubbles released at diffusor per unit time

*V_g is the gas volume per total volume of the bubble-water mixture in the inner core of the plume (dimensionless).

of specific heat per unit water volume ($\rho_w \kappa$) is constant, and neglecting the heat content of the gas volume, the conservation equation for the heat flux ($\pi b^2 w \rho_w \kappa T$) can be reduced to the corresponding expression for the temperature flux $F_T = \pi b^2 w T$:

$$\frac{d}{dz}(\pi b^2 w T) = 2\alpha\pi b w T_a \quad (°C\ m^2\ s^{-1}) \qquad (6)$$

where T_a is the ambient water temperature given by measured temperature profiles or by the lake model.

Flux of total dissolved solids. For water temperatures close to 4°C, the concentration of dissolved solids, expressed by the salinity S, plays a role in establishing the density stratification. Hence it is necessary to include the mass balance for dissolved solids:

$$\frac{d}{dz}(\pi b^2 w \rho_w S) = 2\alpha\pi b w \rho_a S_a \quad (kg\ m^{-1}\ s^{-1}) \qquad (7)$$

where S_a is the ambient salinity.

Fluxes of dissolved oxygen and nitrogen. There are two gases of interest, molecular oxygen (O_2) and nitrogen (N_2), and two phases, dissolved and gaseous, for each. For each species the gas transfer term appears as a gain (or loss) in the dissolved gas conservation equation and as a loss (or gain) in

TABLE 3*b*. Parameter Approximations

Parameter	Approximation	Units
Bubble slip velocity (Figure 5)	$w_b(r) = w_1(r/r_*)^{1.357}$ $r/r_* < 7.0 \times 10^{-4}$	m s^{-1}
	$w_b(r) = w_2$ $7.0 \times 10^{-4} < r/r_* < 5.1 \times 10^{-3}$	m s^{-1}
	$w_b(r) = w_3(r/r_*)^{0.547}$ $r/r_* > 5.1 \times 10^{-3}$ with $w_1 = 4474$ m s^{-1}; $w_2 = 0.23$ m s^{-1}; $w_3 = 4.202$ m s^{-1}; $r_* = 1$ m	m s^{-1}
Gas transfer coefficient for molecular oxygen and nitrogen (Figure 3)	$\beta_i(r) = 0.6$ m s^{-1} (r/r_*) $(r/r_*) < 6.67 \times 10^{-4}$, i = O, N	m s^{-1}
	$\beta_i(r) = 4 \times 10^{-4}$ m s^{-1} $(r/r_*) > 6.67 \times 10^{-4}$, i = O, N	m s^{-1}
Molecular oxygen solubility constant (Figure 4)	$K_O(T) = K_{O1} + K_{O2}T + K_{O3}T^2$ with $K_{O1} = 2.125$ mol m^{-3} bar^{-1}; $K_{O2} = -0.05021$ mol m^{-3} bar^{-1} $°C^{-1}$; $K_{O3} = 5.77 \times 10^{-4}$ mol m^{-3} bar^{-1} $°C^{-2}$	mol m^{-3} bar^{-1}
Molecular nitrogen solubility constant (Figure 4)	$K_N(T) = K_{N1} + K_{N2}T + K_{N3}T^2$ with $K_{N1} = 1.042$ mol m^{-3} bar^{-1}; $K_{N2} = -0.0245$ mol m^{-3} bar^{-1} $°C^{-1}$; $K_{N3} = 3.171 \times 10^{-4}$ mol m^{-3} bar^{-1} $°C^{-2}$	mol m^{-3} bar^{-1}
Constants		
Entrainment coefficient	$\alpha = 0.11$	
Plume radius ratio	$\lambda = 0.8$	

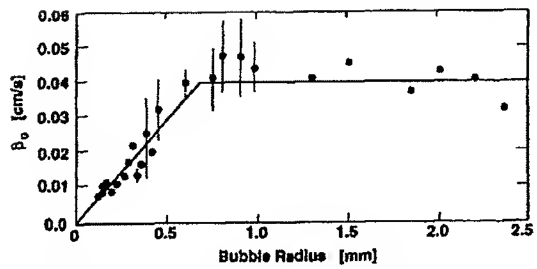

Fig. 3. Mass transfer coefficients β_O for oxygen measured in tap water as a function of bubble radius, based on data (solid circles) compiled by *Motarjemi and Jameson* [1978]. In this model the same mass transfer coefficients for oxygen and nitrogen were used, since the two molecules have nearly identical molecular diffusivities. The solid line shows the parametrization $\beta_O(r) = \beta_N(r)$ used in this paper.

the gas phase conservation equation. The gas flux through bubble surfaces is given by

$$\beta_i(c_{si} - c_i) \quad (\text{mol m}^{-2}\ \text{s}^{-1}) \tag{8}$$

where β_i is the mass transfer coefficient (Figure 3) for the gas species i (O_2 or N_2), c_i is the in situ dissolved gas concentration, and c_{si} is the saturation concentration determined by Henry's law:

$$c_{si} = K_i p_i \quad (\text{mol m}^{-3}) \tag{9}$$

Here p_i is the in situ partial pressure of the gas phase of species i and K_i is the solubility constant (Figure 4).

In order to calculate the total gas transfer per unit height of the bubble plume we use the total number flux of bubbles, N, a quantity which, according to the list of assumptions (see section 2.2, ninth assumption) is determined by the initial conditions (initial bubble radius $r°$, total gas input at diffusor and diffusor depth; Tables 3*a* and 4) and then remains constant within the plume. The number of bubbles per unit plume height is then simply $N/(w + w_b)$, where $(w + w_b)$ is the total bubble velocity (w_b is bubble slip velocity; Figure 5). The total surface area of bubbles per unit plume height is found by multiplying by the area of each bubble, i.e., $4\pi r^2 N/(w + w_b)$. The total gas transfer rate per unit height is then obtained by multiplying this aggregate surface area (per unit height) by the local gas flux:

$$\frac{4\pi r^2 N}{w + w_b}\, \beta_i(K_i p_i - c_i) \quad (\text{mol s}^{-1}\ \text{m}^{-1}) \tag{10}$$

The conservation equation for each dissolved species i, i.e., O_2 and N_2, includes entrainment of ambient lake water (concentrations c_{ia} for i = O and N) and gas exchange:

$$\frac{d}{dz}(\pi b^2 w c_O) = 2\alpha\pi b w c_{Oa} + \frac{4\pi r^2 N}{w + w_b}\beta_O(K_O p_O - c_O) \quad (\text{mol s}^{-1}\ \text{m}^{-1}) \tag{11}$$

$$\frac{d}{dz}(\pi b^2 w c_N) = 2\alpha\pi b w c_{Na} + \frac{4\pi r^2 N}{w + w_b}\beta_N(K_N p_N - c_N) \quad (\text{mol s}^{-1}\ \text{m}^{-1}) \tag{12}$$

Fluxes of gaseous oxygen and nitrogen. The rate of change of advective flux of gaseous O_2 and N_2 is equal to the rate of dissolution or stripping as determined above:

$$\frac{d}{dz}[\pi b^2\lambda^2(w + w_b)m_O] = -\frac{4\pi r^2 N}{w + w_b}\beta_O(K_O p_O - c_O) \quad (\text{mol s}^{-1}\ \text{m}^{-1}) \tag{13}$$

$$\frac{d}{dz}[\pi b^2\lambda^2(w + w_b)m_N] = -\frac{4\pi r^2 N}{w + w_b}\beta_N(K_N p_N - c_N) \quad (\text{mol s}^{-1}\ \text{m}^{-1}) \tag{14}$$

(m_O and m_N are the gaseous concentration of the species per unit bulk volume of the bubble-water mixture). Note that the relevant volume flux for the gaseous components contains the total bubble velocity, $w + w_b$, and the reduced plume radius, λb. Upon solving these equations it is found that the proportion of O_2 and N_2 in the rising gas bubbles is changing. For instance, pure O_2 bubbles will strip N_2 from the water column at the same time that O_2 is being dissolved.

The assumptions made in developing these eight equations could be generalized, but at the price of adding parameters. For instance, one could distinguish five separate top hat radii for velocity, bubbles, dissolved gases, temperature, and salinity (giving four different λ ratios). The refinement is not warranted at this time, since information is lacking on how to select different λ values. Hence, we use only two top hat radii: b for velocity, temperature, salinity, and dissolved gases, and λb for bubbles. It is well known from previous investigations that λ is significantly less than 1, and probably about 0.8 [*Milgram*, 1983].

2.4. *Variable Transformation*

To simplify the solution we let the basic dependent variables be the eight integrated fluxes defined in Table 2, namely those for water volume, momentum, temperature, dissolved solids and the dissolved and gaseous phases of molecular O_2 and N_2. With these definitions, the eight conservation equations ((4)–(7) and (11)–(14)) may be rewritten in terms of the new variables:

$$\frac{d\mu}{dz} = 2\alpha(\pi M)^{1/2} \tag{15}$$

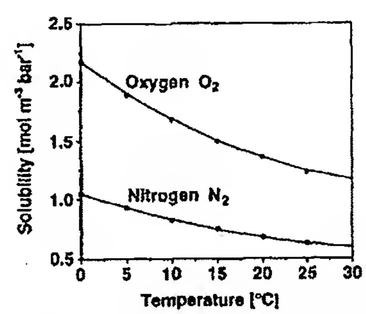

Fig. 4. Solubility constants K_i of molecular nitrogen and oxygen as functions of temperature. Dots represent values taken from *Marshall* [1976]. Solid lines show second order polynomial fits used in this model.

TABLE 4. Initial Conditions for Bubble Plume Calculation

Initial Plume Variable	Symbol	Method for Determining Initial Value
Plume radius	b°	effective radius of the entire diffusor unit (diffusor geometry)
Vertical plume velocity	w°	w° depends on source and plume properties; see section 2.5
Volume flux of plume water	μ°	$\mu^\circ = \pi b^{\circ 2} w^\circ$
Momentum flux	M°	$M^\circ = \pi b^{\circ 2} w^{\circ 2}$
Temperature	T°	ambient temperature at diffusor depth
Temperature flux	F_T°	$F_T^\circ = \mu^\circ T^\circ$
Dissolved species		
Concentrations	S°, c_O°, c_N°	ambient concentrations at diffusor depth
Fluxes	F_S°, D_O°, D_N°	$F_S^\circ = \mu^\circ S^\circ$, $D_O^\circ = \mu^\circ c_O^\circ$, $D_N^\circ = \mu^\circ c_N^\circ$
Gas fluxes	G_N°, G_O°	nitrogen and/or oxygen input rate (mode of operation)
Bubble radius*	r°	design (material and porosity) of diffusor
Pressure	p°	depth of diffusor (topography and installation) and ambient density profile
Number flux of bubbles†	N°	initial gas fluxes, bubble radius and pressure at the diffusor depth (Table 3*a*)

*It may be possible to vary bubble radius during operation by switching between different installed diffusor tubes. For the system "Tanytarsus" a switch between small (oxygenation mode) and large (artificial mixing mode) bubbles is possible.
†The number flux of bubbles, $N(z)$, is kept constant in the plume: $N(z) = N^\circ$.

$$\frac{dM}{dz} = \frac{\rho_a - \rho_p}{\rho_p} g\lambda^2 \frac{\mu^2}{M} + \frac{\rho_a - \rho_w}{\rho_p} g \frac{\mu^2}{M}(1 - \lambda^2) \tag{16}$$

$$\frac{dF_T}{dz} = 2\alpha(\pi M)^{1/2} T_a \tag{17}$$

$$\frac{dF_S}{dz} = 2\alpha(\pi M)^{1/2} \rho_a S_a \tag{18}$$

$$\frac{dD_O}{dz} = 2\alpha(\pi M)^{1/2} c_{Oa} + \frac{4\pi r^2 N}{(M/\mu) + w_b} \beta_O\left(K_O p_O - \frac{D_O}{\mu}\right) \tag{19}$$

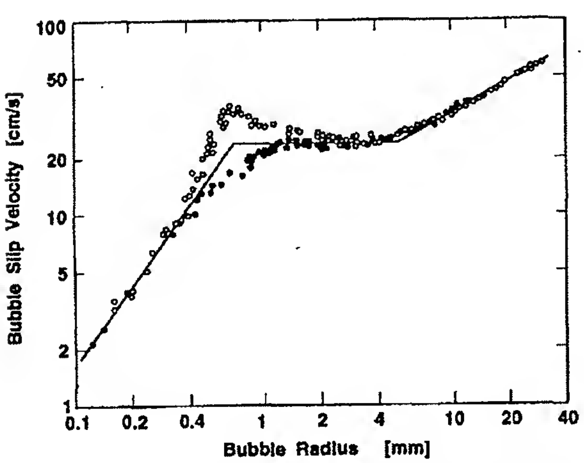

Fig. 5. Terminal slip velocity of air bubbles, w_b, measured in tap water (solid circles) and distilled water (open circles) [*Haberman and Morton*, 1954]. The solid line represents the approximation used in this model.

$$\frac{dD_N}{dz} = 2\alpha(\pi M)^{1/2} c_{Na} + \frac{4\pi r^2 N}{(M/\mu) + w_b} \beta_N\left(K_N p_N - \frac{D_N}{\mu}\right) \tag{20}$$

$$\frac{dG_O}{dz} = -\frac{4\pi r^2 N}{(M/\mu) + w_b} \beta_O\left(K_O p_O - \frac{D_O}{\mu}\right) \tag{21}$$

$$\frac{dG_N}{dz} = -\frac{4\pi r^2 N}{(M/\mu) + w_b} \beta_N\left(K_N p_N - \frac{D_N}{\mu}\right) \tag{22}$$

This is a set of eight coupled nonlinear first-order differential equations which can be integrated numerically. The system contains five additional variables (ρ_p, ρ_w, r, p_O, p_N) which are linked to basic variables by equations of state (Table 3*a*) and thus can be adjusted after every integration step. Furthermore, there are other physicochemical parameters which are either kept constant throughout the model calculation (e.g., relative bubble plume radius λ, entrainment coefficient α) or can be calculated from empirical approximations (Table 3*b*). The number flux of bubbles N is established by the initial gas volume flux and the assumed initial bubble radius, and then remains constant within the plume.

2.5. *Initial Conditions*

The model calculations depend crucially on both the initial plume conditions, which are summarized in Table 4, and the ambient lake water profiles. Whereas the ambient profiles are given by the state of the lake (influenced however by the plume operation in the long term, see section 2.7), the initial conditions can be controlled to a certain extent by the design and operation of the diffusor units.

We have to specify the initial values of the eight flux variables defined in Table 2. According to the eleventh assumption, the initial values of temperature T°, salinity S°, dissolved O_2 concentration c_O and dissolved N_2 concentra-

tion c_N° are given by the ambient lake water characteristics at the depth of the diffusor. However, to determine the respective initial fluxes we need to multiply each by the initial volume flux μ° which is discussed below. The gaseous O_2 and N_2 fluxes, G_O° and G_N°, are the key initial variables to be controlled by the mode of operation of the diffusor. The initial bubble radius, r°, is determined mainly by the design of the diffusor (pore size) and cannot be controlled by varying the gas flow rate (unless it is very large). The number flux of bubbles, $N = N^\circ$, kept constant in the whole plume, is determined by total gas flux, $G_O^\circ + G_N^\circ$, initial bubble radius, r°, and pressure, p° (Table 3*a*), and is not an independent initial condition.

The initial inner plume radius (λb°) is determined by the apparent size of the bubble source area. Specifying λ and b° establishes the width of the velocity plume. In practice, a diffusor unit may consist of several diffusor tubes distributed in a starlike pattern of six arms, as shown in Figure 1*b* [*Stadelmann*, 1988]. In such cases we consider the area of the entire diffusor unit as a uniform source of buoyancy and consequently set the initial plume area $\pi(\lambda b^\circ)^2$ equal to the circular area covered by the tubes.

Mathematically, the vertical velocity w° is an additional independent initial variable. In reality, however, the initial water velocity should be determined by the properties of the source and of the ambient water. It has been found useful to define a densimetric Froude number (dimensionless) as

$$Fr = \frac{w}{[2\lambda bg(\rho_a - \rho_p)/\rho_p]^{1/2}} \tag{23}$$

For a single-phase plume Fr is simply inversely proportional to the local Richardson number Ri [*Fischer et al.*, 1979] which has the unique value of 0.557 along the plume, except near the source. The constant of proportionality depends on the type of plume profiles being used; here $Fr = (\pi/4)^{1/4}Ri^{-1}$. Thus the Froude number of the plume should everywhere have a value of 1.69, except near the source. However, for bubble plumes there is an additional characteristic velocity, the bubble slip velocity w_b. Thus we do not expect a unique starting condition to exist. For very small bubbles ($w_b \rightarrow 0$), the initial Froude number should be the same as for a single-phase plume. From the model calculations that follow we find that as z increases, Fr does indeed tend to a nearly constant value of about 1.7. For initial values of $Fr^\circ < 1.5$, the plume water velocity w initially (immediately above the diffusor) increases with increasing z (reasonable behavior), while for $Fr^\circ > 1.5$, w first decreases in the model (unlikely). Therefore, for the standard case (section 3.1) we use the value in between, namely, $Fr^\circ = 1.6$, and for the sensitivity analysis (section 3.2) we analyze the effect of varying Fr° values.

2.6. *Solution Procedure*

The stationary solution for the flux variables (Table 2) is calculated by a three-step iteration loop. In the first step the eight differential flux equations ((15)–(22)) are integrated using the standard first-order Euler method, starting from the initial values listed in Table 4. The vertical coordinate increment dz is controlled by keeping the maximum relative change of the flux variables below a chosen value (1‰). By sensitivity analysis it was found that the 1‰ criterion is sufficiently small to guarantee that the final values of the plume variables (Table 1) are not increment dependent (<1‰ relative error). After each iteration the equations of state (Table 3*a*) are solved for the partial pressure of O_2 and N_2 (p_O, p_N), the water and plume densities (ρ_w, ρ_p), and the bubble radius (r). In the third and last step, the remaining parameters, bubble slip velocity, w_b (Figure 5), mass transfer coefficients, β_i (Figure 3), and the solubility constants, K_O and K_N (Figure 4), are calculated from the parameterization listed in Table 3*b*.

The iteration is interrupted and the program stopped when the plume velocity approaches zero or when the plume reaches the surface. Comparison of the final plume water density with the ambient density profile then allows the determination of the equilibrium depth, i.e., the depth to which the plume water would sink back if no further mixing occurred. However, the fallback plume (which we do not attempt to model) entrains some additional water on the way down; as a result, in reality it does not fall back completely to the calculated equilibrium depth.

2.7. *Plume Model in Relation to Lake Model*

The plume model is only one component of the overall lake model. In the simplest case, the lake is considered to consist of two parts: the small plume zone (one or more vertical columns) and the much larger lake zone outside the plumes (Figure 1*a*). The lake zone may in many cases be considered to be horizontally well mixed or uniform in properties (such as temperature T or dissolved O_2); i.e., $T_a(x, y, z, t) = T_a(z, t)$.

The plume is assumed to be in quasi-steady state, operating for some period of time Δt (of the order of days) with essentially fixed ambient environmental profiles determined by the lake zone. Then the lake zone profiles are adjusted to reflect the results of the plume action over the given time period Δt. In other words, the ambient profiles change so slowly that they may be considered piecewise constant for the purpose of the plume calculations.

The presentation of the lake zone model is not the purpose of this paper. However, for just the physical aspects, the basic equations for coupling to the plume model are conservation of water mass and conservation of any scalar species or pollutant. For conservation of water mass at level z, the vertical rate of change of the vertical flow, wA, through the lake cross section A (w is far-field vertical upward velocity, Figure 1*a*), is equal to the plume outflow per unit height $q_p(z)$ minus the plume entrainment $q_e(z)$:

$$\frac{d(wA)}{dz} = q_p - q_e \quad (\mathrm{m^2\ s^{-1}}) \tag{24}$$

By definition, either one or the other of q_p and q_e must be zero at a particular level z; i.e., the plume is either entraining ($q_p = 0$) or detraining ($q_e = 0$).

In the far field of the lake the mass balance of any conservative substance with concentration $c_a(z)$ is given by

$$A\frac{\partial c_a}{\partial t} + \frac{\partial(c_a wA)}{\partial z} = q_p c_p - q_e c_a \quad (\mathrm{mol\ s^{-1}\ m^{-1}}) \tag{25}$$

where c_a and c_p describe ambient and mean plume concentrations, respectively.

The plume model uses $c_a(z)$ (and $T_a(z)$) as inputs, and produces q_p, q_e, and c_p as outputs (Figure 1*a*) which are used to compute new values of w and c_p at given time

TABLE 5. Characteristics of Internal Lake Restoration Measures in Baldeggersee (Switzerland)

Parameter	Value or Description
	Lake Data
Location	47°12′N, 8°16′E, (15 km north of Lucerne, Switzerland)
Surface altitude	462 m above sea level
Surface area	5.2 km^2
Volume	176 × 10^6 m^3
Maximum depth	66 m
	Oxygenation Mode (May–October)
Operation	four to six diffusors at depth between 42 and 64 m
Total O_2 input	3–4.5 × 10^3 kg d^{-1} 0.025–0.037 N m^3 s^{-1}*
O_2 input per diffusor unit	~0.005–0.007 N m^3 s^{-1}
	Artificial Mixing Mode (November–April)
Operation	three to four diffusors or nozzles at depth between 58 and 64 m
Total air input	0.056 N m^3 s^{-1}
Air input per diffusor unit	0.014–0.017 N m^3 s^{-1}

*1 N m^3 = 1 m^3 of gas at 1 bar and 0°C.

intervals Δt by finite difference equations representing the lake model (equations (24) and (25)). This procedure was demonstrated by *Imboden* [1985].

3. THE CASE OF BALDEGGERSEE: APPLICATION AND SENSITIVITY EVALUATION OF THE MODEL

In this section application of the model to Baldeggersee, a highly eutrophic lake (Table 5), is described. Among all Swiss lakes, Baldeggersee has the longest record of artificial oxygen and air input [*Imboden*, 1985]. Artificial destratification with an air bubble plume began in February 1982 followed by a first experimental oxygenation of the hypolimnion using pure oxygen during the next summer.

Vertical profiles of O_2, temperature and salinity measured in July 1983 (oxygenation) and November 1983 (artificial mixing) are chosen as the input data to run the bubble plume model (Figure 6). Measured N_2 profiles in Baldeggersee were approximately constant and close to the surface saturation value in winter. Hence a constant value of $c_N = 0.71$ mol m^{-3} (20 g m^{-3}), corresponding to N_2 saturation at $T =$ 4°C at the altitude of Baldeggersee, was taken as the ambient N_2 concentration. It is assumed that the density of the water is defined only by the temperature and the concentration of dissolved solids, which consist mainly of Ca^{2+} and HCO_3^-. The influence of dissolved solids on the vertical density gradient is negligible in the thermocline of most lakes, although in the prerestoration period chemical density gradients in the deep hypolimnion may be important as well [*Joller*, 1985]. The ambient density profiles for July and November 1983 shown in Figure 6*d* were calculated from water temperature and electrical conductivity using the modified equations given by *Bührer and Ambühl* [1975] (Table 3*a*).

3.1. *The Standard Cases*

The model calculations are based on two standard situations as listed in Table 6. Since the initial values of plume size, vertical plume velocity and bubble radius are not exactly known, reasonable values for the standard cases

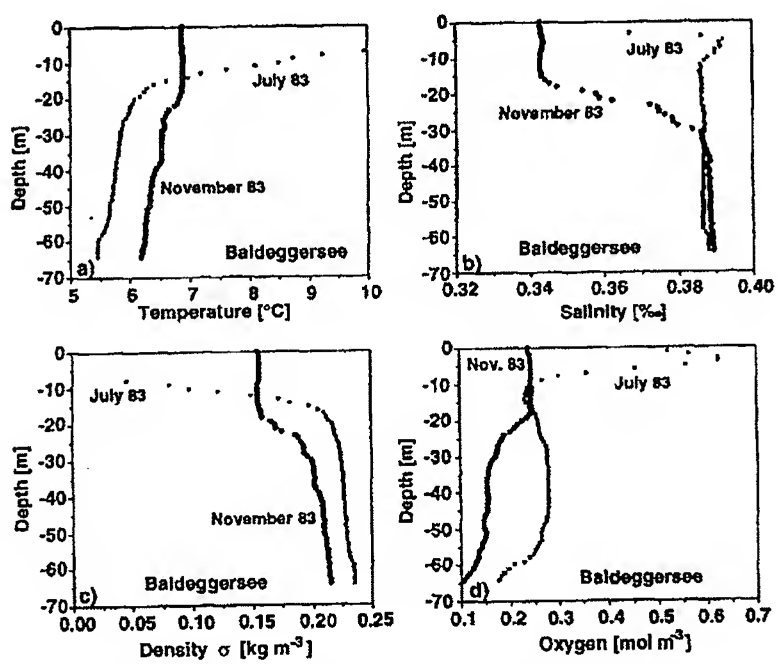

Fig. 6. Temperature, salinity, density ($\sigma = \rho - 1000$ kg m^{-3}), and oxygen profiles, measured in July (solid squares) and November (open circles) 1983 in Baldeggersee. These profiles serve as input data for the two standard case model calculations.

TABLE 6. Model Input Values for One Diffusor Unit, Applied to Standard Case and Sensitivity Analysis

Parameter		Standard Case	Sensitivity Analysis
Diffusor depth, m	z^o	65	n.v.*
Initial plume size, m^2	πb^{o2}	20	0–50
Entrainment factor	α	0.11	0.05–0.2
	Oxygenation		
O_2 input,† $N\ m^3\ s^{-1}$		0.0062	0.001–0.1
Initial Froude number‡	Fr^o	1.6 (w^0 = 0.125 m/s)	1.0–2.0
Initial bubble radius, m	r^o	0.001	10^{-4} to 10^{-1}
Temperature, salinity and oxygen profiles		July 1983 (Figure 6)	n.v.
	Artificial Mixing		
Air input,† $N\ m^3/s$		0.014	n.v.
Initial Froude number‡	Fr^o	1.6 (w^0 = 0.172 m/s)	0.5–2.5
Initial bubble radius, m	r^o	0.006	n.v.
Temperature, salinity and oxygen profiles		Nov. 1983 (Figure 6)	n.v.

*Here n.v. denotes not varied.
†1 $N\ m^3$ = 1 m^3 of gas at 1 bar and 0°C.
‡See section 2.5 for the choice of the initial Froude number, equation (23).

were selected followed by a sensitivity analysis of the model results with respect to these choices. The calculated vertical variations of important model variables along the plume are shown in Figure 7 for both modes of operation, i.e., pure oxygen input during the summer and air input during the winter.

The most important difference between the two cases (Table 6) lies in the initial bubble radius, i.e., 1 mm in July versus 6 mm in November. During oxygenation (July) the surface-to-volume ratio of the bubbles is large. The bubbles dissolve quickly and their volume is only 0.1% of the initial value at about 40 m depth (Figure 7*c*). When the bubbles disappear, the colder and heavier water from the lake bottom loses its buoyancy (Figure 7*e*), the plume stops (Figure 7*a*), disperses, sinks part way, and merges with the surrounding lake water at the depth of neutral density. The model calculation is restricted to the zone where the plume is still rising. At the depth of maximum plume rise (DMPR) some

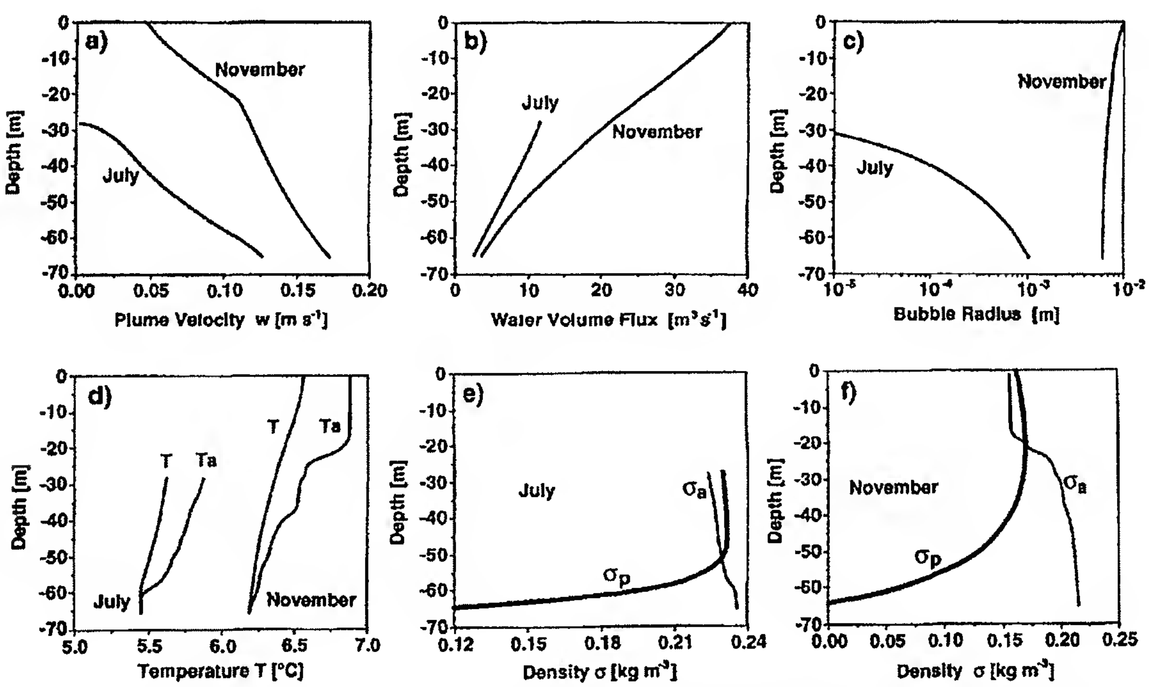

Fig. 7. Model calculations for bubble plumes in Baldeggersee using standard parameters from Table 6 and ambient profiles from Figure 6. Profiles of important model variables along the vertical plume axis are shown for the two modes of operation: oxygenation during summer (July) and artificial mixing with compressed air during winter (November).

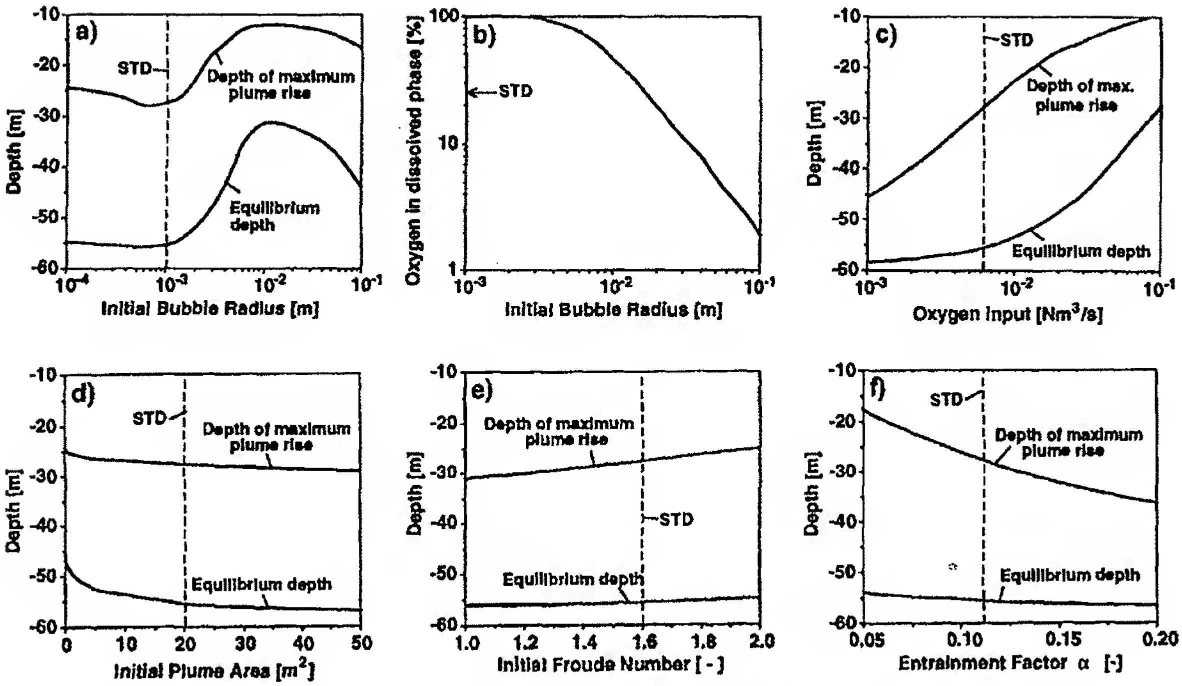

Fig. 8. Sensitivity of plume model calculated for the case of oxygen input into Baldeggersee using the standard situation of July 1983 (Table 6). Only one parameter is varied from its standard value (labeled by "STD") for each calculation. See text for definition of equilibrium depth.

bubbles may still exist if the system operates with large enough bubbles. Possible further dissolution or secondary plume creation [*McDougall*, 1978] by the escaping bubbles above DMPR is not considered in this model. If small bubbles are used, however, they disappear before the DMPR is reached. In the momentum overshoot phase of negative buoyancy no secondary plumes have to be considered; the plume then behaves as an ordinary one [*Morton et al.*, 1956].

In contrast, during artificial mixing with air (November), gas exchange is slower since the bubbles have a larger initial radius. The rate of increase in bubble size due to decompression is similar to the rate of decrease due to dissolution. The net effect, however, is a slight increase in the in situ bubble radius (Figure 7*c*). Therefore, the plume retains its buoyancy up to 20 m below the lake surface (Figure 7*f*). The remaining momentum brings the plume to the surface (Figures 7*a* and 7*b*).

Note that the differences between the summer and winter cases are primarily related to the different initial bubble sizes; the chemical composition of the bubbles (oxygen or air, respectively) is less important for deep lakes since the high hydrostatic in situ pressure makes the gas exchange rate nearly independent of the ambient dissolved gas concentration at this depth.

The larger size of the bubbles is not the only reason why, in the artificial mixing case, the plume reaches the surface. Higher gas flux and weaker ambient stratification also support stronger plumes. Higher gas flux leads to a larger density difference (i.e., buoyancy), and a higher initial plume velocity (momentum flux). The weak stratification of the water column provides little negative buoyancy to stop the plume. The effects of initial gas flux and bubble size on the plume will be investigated in the following sensitivity analysis.

3.2. *Sensitivity Analysis*

With respect to the application of the model to internal lake restoration the most important model characteristics are the vertical extension of the plume, the magnitude of the induced vertical volume flux of water, and the fraction of oxygen transferred to the dissolved phase. It is therefore important to investigate the sensitivity of these quantities with respect to those input parameters which either can be influenced by the design of the diffusor system or are not well known from field observations. It is not easy to compare different model results for the winter case in a didactically clear way, since, depending on the parameters, the modeled plumes may or may not reach the surface. Therefore the following sensitivity analysis refers only to the summer case, which allows easier comparison (Figure 8). For each calculation, all parameters except the one which is varied correspond to the standard case (Table 6).

Among all the parameters, initial bubble size and initial gas flow have the largest influence on the behavior of the bubble plume, especially on the depth of maximum plume rise (DMPR). If the initial bubble radius is less than 1 mm, the DMPR is about 25–28 m and is nearly independent of bubble size (Figure 8*a*). For larger bubbles, the DMPR becomes shallower and the plume reaches its highest level for a radius of about 1 cm. The curve (Figure 8*a*) can be qualitatively explained in terms of the size dependence of the

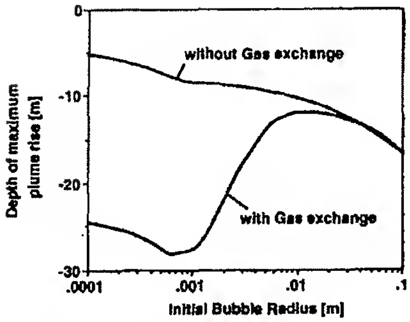

Fig. 9. Maximum plume rise calculated as a function of initial bubble size for the standard situation of July 1983 with and without gas exchange (i.e., dissolution of bubbles). Plume dynamics is strongly dependent on dissolution for bubbles of radius smaller than about 5 mm.

gas exchange and bubble slip velocity alone. Since the gas exchange rate (fractional volume changes per unit time) depends on the surface-to-volume ratio of the bubbles, the oxygen dissolves faster in the lake if the bubbles are small. In addition, smaller bubbles have lower slip velocities and thus a longer contact time with the water before reaching the DMPR.

For bubbles with a radius of less than about 0.7 mm, the exchange rate (fractional volume changes per unit time) is approximately independent of bubble size, since the transfer velocity is proportional to bubble radius, whereas the surface-to-volume ratio is inversely proportional to bubble radius (Table 3*b* and Figure 3). As a consequence, the smaller and slower the bubbles are, the more buoyancy is generated and the longer the buoyancy lasts. This causes the plume to rise higher. Bubbles with a radius greater than about 0.7 mm have decreasing gas exchange rates per unit volume (since the transfer rate is constant) and constant slip velocities up to a radius of 5 mm. The height of the plume will consequently increase with bubble size. For bubbles with a radius greater than about 10 mm, the height of the plume decreases again since dissolution no longer has any influence (Figure 9). The bubbles rise so rapidly that the buoyancy (proportional to $(w + w_b)^{-1}$) is significantly diminished; the bubbles escape the DMPR and start a new plume (not described by the model).

Because pure oxygen is expensive it is of major importance to operate a lake oxygenation system so as to minimize the amount of oxygen lost by escaping bubbles and to deliver the oxygen as exactly as possible to the required depths. As shown in Figure 8*b*, for bubbles with a radius of less than 3 mm, more than 99% of the O_2 dissolves. For bubbles with a radius of 3 mm, vertical water circulation reaches a maximum while no O_2 bubbles escape from the hypolimnion. For larger bubbles the total transfer rate decreases rapidly to reach a value of less than 10% for a radius greater than about 3 cm.

The oxygen input rate directly influences the density and thus the buoyancy of the plume. As seen in Figure 8*c*, an increase in the O_2 input rate from 10^{-3} to 10^{-1} N m^3 s^{-1} causes the DMPR to rise from 45 m to 10 m depth. For large O_2 input rates the DMPR is determined mainly by the position of the thermocline, i.e., the zone of maximum density gradient. If the total oxygen flow rate and the plume intrusion depth range are prescribed, the model allows the determination of the minimum number of diffusor units needed to reoxygenate at the desired depths. For example, if the oxygen input per diffusor is reduced to 50% (e.g., by doubling the number of diffusors in the lake), the DMPR sinks by 8 m (Figure 8*c*). Likewise, for artificial mixing with air bubbles, the model can be used to find the optimal bubble size and the minimum airflow rate as a function of the number of diffusors, provided that the ambient stratification and the turnover rate are given.

The initial plume size and initial Froude number (or water velocity), two parameters which are difficult to estimate without additional and complicated field measurements, do not have a significant influence on the DMPR (Figures 8*d* and 8*e*). The initial plume size cannot vary more than between about half the diffusor area (10 m^2) and twice this area (40 m^2). The initial plume velocity is expected to correspond approximately to a densimetric Froude number of 1.6, which we choose slightly smaller than the apparent asymptotic value in the near field of 1.7. The low sensitivity of the model calculation with respect to these two parameters means that during oxygenation the properties of the plume are determined mainly by the plume's dynamics and not by the initial conditions.

As mentioned above, the entrainment factor is an empirical constant which has been determined in several laboratory experiments [*Milgram*, 1983]. A typical value for Gaussian profiles is 0.08, which is equivalent to 0.11 for top hat profiles. Since the entrainment of surrounding water decelerates the water plume, the DMPR depends strongly on this factor (Figure 8*f*).

Bubble dissolution has a drastic effect on plume dynamics. In Figure 9 the calculated DMPR is shown as a function of initial bubble size with and without gas exchange, respectively. Since small bubbles dissolve faster and have lower slip velocities than large ones, the effect of dissolution on the DMPR is most prominent for small bubbles. For radii larger than about 2 cm, dissolution can be ignored. The result dramatically shows the importance of gas exchange for bubble plume models, if the initial bubble radius is less than about 5 mm, in deep water (65 m depth in this example).

3.3. *Artificial Tracer Experiment*

On August 22/23, 1983, in collaboration with the Institute of Geography of the University of Bern, a tracer experiment was conducted in Baldeggersee. During a period of 10 min, 1.5 kg of uranin, a fluorescent dye which had previously been dissolved in 200 L of water taken from the lake bottom, was introduced into the plume at a depth of 57 m, just above one of the diffusors, which at this time was releasing 0.0083 N m^3 s^{-1} of O_2. The tracer was pumped from a platform into a hose fixed to the diffusor unit. The temporal evolution of the dye cloud was then measured using an in situ fluorometer operated from the platform.

During the initial phase of the experiment, part of the dye rose up to a depth of 5 m. The average rising velocity was 0.16 m s^{-1} below 40 m depth, and about 0.04 m s^{-1} above this depth (Table 7). After 12 hours, most of the uranin was found between 10 and 23 m depth (Figure 10); a small amount was found below this layer.

Since the parameter to which the model is most sensitive, namely, the initial bubble radius $r°$, is not very well known,

TABLE 7. Uranin Experiment and Model Calculation, August 1983

	Model*	Field Experiment
Depth of maximum dye rise (above plume), m		5
Depth of maximum plume rise, m	13–11	
Depth of tracer insertion, m		10–23
Equilibrium depth,† m	30–25	
Plume velocity, m/s		
57–40 m depth	0.12–0.13	0.16
40–14 m depth	0.06–0.08	
40–5 m depth		~0.04

*Parameters: initial bubble radius, 2–4 mm; initial plume velocity, 0.15 m/s (Fr° = 1.6); oxygen flow, 0.0083 N m^3 s^{-1}; depth of diffusor, 57 m; initial cross-sectional area, 20 m^2; initial plume radius, 2.52 m; ambient profiles, July 1983 (Figure 6).

†Depth to which the plume water sinks back once it has lost all momentum. The model value was calculated by assuming that no entrainment of ambient water into the plume occurs once the plume has reached its highest level. Therefore, the value given represents a maximum value.

a rigorous test of the model is not possible. However, model results are found to agree reasonably well with observation if r° is taken to lie within the range 2–4 mm (Table 7). Based on visual inspection of the bubbles leaving the diffusor tubes and on the fact that ≲1% of the oxygen escaped to the surface, the actual size of r° was estimated to lie within this range. In the lower part of the plume, the observed upward velocity of the dye was close to the modeled plume velocity. In the upper part, the upward velocity of the dye was lower than the modeled plume velocity, and the dye was found to rise to a greater height than that predicted by the model. We presume that small secondary plumes generated by undissolved bubbles remaining after the main plume has stopped rising carried part of the dye up to a depth of 5 m, resulting in a relatively low apparent upward velocity (Table 7). The fact that the tracer was later detected in the lake mainly between the modeled DMPR (11–13 m) and the modeled equilibrium depth (30–25 m) supports this interpretation. Plume water appears to have mixed with the surrounding water at different rates during the sinking phase. Detailed tests of the model are planned for newer diffusor systems.

4. DISCUSSION

In this section the model is discussed and compared with the results of other investigations in order to explore the range of its validity and to identify open questions.

1. The scientific literature contains just a few experimental data sets which are suitable for comparing model calculations with measurements. The hydrodynamic part of the model was tested by comparing model results with data from the Bugg Spring experiment of *Milgram* [1983]. In this experiment air was injected at 50 m depth through a nozzle of comparatively small area (about 10^{-2} m^2) into a nonstratified system. The model was run with entrainment factors α_{th} = 0.116 determined from the observed value α_g and adapted to the top hat distribution by putting $\alpha_{th} = \sqrt{2}\alpha_g$. Calculated and observed values for volume flux, plume radius and plume velocity agreed within 10% everywhere within the vertical profile. The model calculations are also close to the proportionality between plume water volume flux μ and the square root of the airflow rate observed by *Leitch and Baines* [1989]. Since bubble dissolution was not important in their experiment, the bubble solution dynamics was tested by comparison with the experiments of *Motarjemi and Jameson* [1978] in which bubbles of different sizes were released at 10 m depth. Calculated and observed dissolution rates were equal to within a few percent.

2. In this model we do not distinguish between the zone of flow establishment and the zone of the fully developed plume. We also neglect the initial adjustment of the bubble slip velocity just above the diffusor. We try to reduce this insufficiency of the model by choosing appropriate initial plume velocities. There are physical arguments for reducing the range of the initial Froude number Fr°. As displayed in Figure 11 for the case of an unstratified water column, the Froude number (equation (23)) approaches a maximum value of $Fr \approx 1.7$ at about 15–25 m above the diffusor for all initial Froude numbers less than 1.7. In fact, any initial value of Fr°

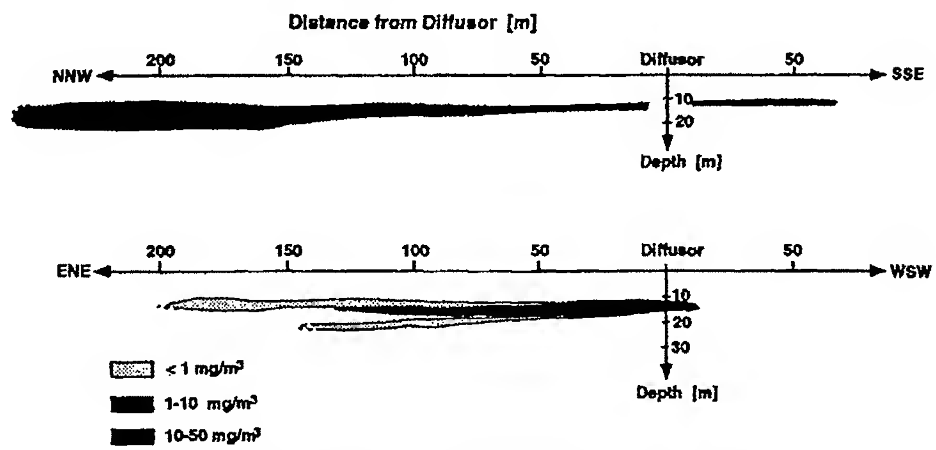

Fig. 10. Distribution of uranin in Baldeggersee 12 hours after injection into the bubble plume just above the diffusor at 57 m depth. The two diagrams show tracer concentration along two mutually perpendicular transects. Most of the uranin is dispersed between 10 m and 23 m depth. (Courtesy of Naturaqua, Bern, Switzerland.)

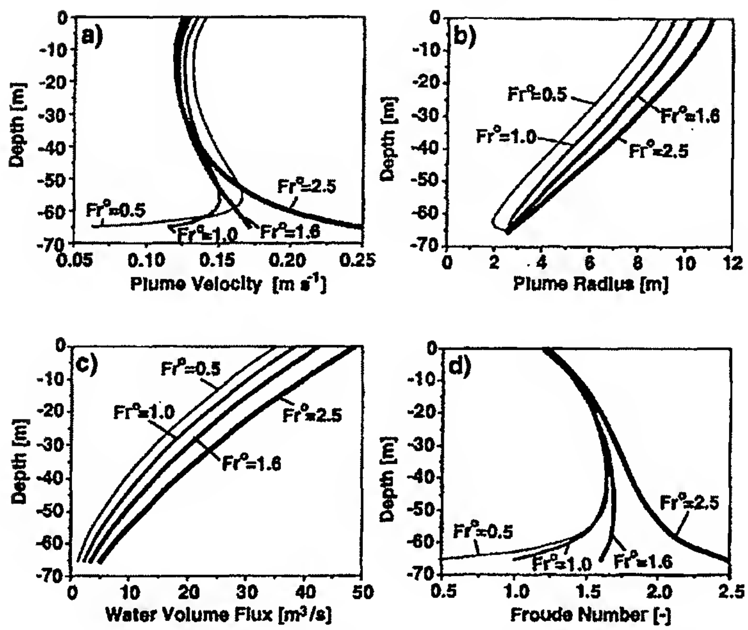

Fig. 11. Plume velocity and radius, volume flux and local Froude number Fr as functions of depth in unstratified water calculated with standard parameters for artificial mixing (Table 6) for various initial Froude numbers Fr° (Fr° labeled on curves). Note the contraction and acceleration of the plume for $Fr^\circ < 1.0$ and the asymptotic behavior of Fr for $Fr^\circ < 1.7$.

> 1.7 is unrealistic because the plume would have to undergo a decrease in velocity immediately above the diffusor (just where bubbles enter the flow), as can be seen in Figure 11*a* for the case $Fr^\circ = 2.5$. For $Fr^\circ < 1.5$ the plume is accelerated immediately above the diffusor, as demonstrated in Figure 11*a* for the case $Fr^\circ = 1.0$. For $Fr^\circ \lesssim 1.0$ the plume initially undergoes contraction as it rises (Figure 11*b*). This contraction becomes more pronounced as Fr° decreases to 0.5. Because a slight contraction can be observed in tank experiments [*Müller et al.*, 1987], we regard values of 0.75–1.0 as a reasonable lower bound for Fr°.

The initial Froude number Fr° depends most likely on the geometry of the diffusor source, since for the zone of flow establishment it is relevant whether the water can flow upward through the diffusor area (open source, diffusor above the bed) or whether the water has to flow horizontally to the rising plume (closed source, diffusor resting on the bed). It seems likely that in the latter case the initial Froude number Fr° will be smaller. Because the slight contraction which was observed in tank experiments occurred for a closed source [*Müller et al.*, 1987] and because the lake restoration diffusor unit with widely spaced tubes represents an open source, we conclude that the initial Froude number for the latter lies between 1.0 and 1.7.

3. We assumed top hat distributions for all plume properties. Mathematically, the scaling involved here is nearly equivalent to that inherent in the horizontally integrated model, presented by *Ditmars and Cederwall* [1974]. It simplifies the model, but does not restrict its dynamic generality, as long as the profiles (of velocity and buoyancy) remain similar at all heights. We introduced λ, the ratio of the inner plume radius (containing the bubbles) to the velocity radius, as the only plume geometry parameter. However, as long as the water velocities in the bubble core and the outer annulus are equal, the model is independent of λ, as is evident from (16). We retained λ in this model, however, in order to obtain the correct equations for O_2 and N_2 if the double plume model [*McDougall*, 1978] is used.

4. In the case of strong stratification, single-phase plume models do not adequately describe the plume if the bubbles are not completely dissolved at the predicted depth of maximum plume rise. Bubble plume experiments carried out by *McDougall* [1978] in a stratified tank showed that fluid from the outer annulus can leave the plume at levels of neutral buoyancy and spread out horizontally, while the center of the plume, where all the bubbles are concentrated, continues to rise. The present model disregards the double plume structure, the detrainment, and the development of secondary plumes initiated by the remaining bubbles. Secondary plumes are created when oxygenation is carried out with relatively large bubbles which are not yet dissolved at DMPR, or in the case of artificial mixing, when the airflow rate is not large enough to bring the entire plume to the surface. For such situations, the model presented here loses its validity as soon as the water has lost its vertical momentum. However, oxygen input with adequately small bubbles which disappear completely (Figures 7*c* and 7*e*) will not generate secondary plumes. The price for using the double plume model is the addition of a further two entrainment factors.

5. The entrainment coefficient α is not a constant for all plumes. A simple parameterization is not obvious. In our model for the standard case $\alpha_{th} = \sqrt{2}\alpha_g = 0.11$ was used, corresponding to $\alpha_g = 0.08$ as given by *Fischer et al.* [1979]. *Milgram* [1983] calculated α for bubble plumes of various scales based on data from several authors and correlated

these values with a "bubble Froude number F_B" defined by local plume properties. *Milgram*'s [1983] values for α_{th} averaged 0.081 and 0.12 for airflow rates of 0.024 and 0.118 N m^3 s^{-1}, respectively, for the 50-m-deep Bugg Spring experiment. *Fannelop and Sjoen* [1980] observed values of α_{th} from 0.10 to 0.14, increasing with airflow rates in the range 0.005–0.022 N m^3 s^{-1}.

6. In the conservation equations used here, vertical turbulent flux terms (such as $w'c'$) are neglected compared to fluxes based on mean properties, presuming that the former are small compared to the latter. This assumption is equivalent to a momentum amplification factor of $\gamma = 1$ [*Milgram*, 1983]. The analysis of *Milgram* [1983, Table 1] yielded values of γ = 1.0–1.1 for typical oxygenation gas rates and γ = 1.1–1.26 for gas rates appropriate to artificial mixing. The corresponding overestimation of the momentum gain would consequently be not more than 21%. However, *Milgram* [1983] has shown that for plumes with low bubble density, γ can increase dramatically.

7. There are many questions concerning bubble plumes still remaining open which will have to be addressed in tank and field experiments. Apart from the problems raised in the discussion above, we would like to mention the question of how bubble size affects bubble dynamics [*Müller et al.*, 1987], the problem of continuous detrainment and problems related to the interaction of the plume with the ambient flow field in the lake (cross flow, plume wandering). Some of these questions are being investigated in the new bubble-plume tank of the Swiss Federal Institute of Technology [*Müller et al.*, 1987]. We think that the mathematical model presented here provides a useful framework for further investigations and helps to relate laboratory experiments to field situations when bubble dissolution and expansion are important.

5. SUMMARY AND CONCLUSIONS

1. A steady, horizontally averaged plume model was developed based on the entrainment hypothesis, variable buoyancy determined by ambient profiles and actual plume properties, and processes of bubble gas exchange and decompression. The model was applied to a stratified lake for a diffusor system with a large open source and low gas flow rates (of the order of 5 × 10^{-4} N m^3 s^{-1} m^{-2}). Model calculations were in encouraging agreement with experimental data.

2. Gas exchange, decompression and bubble slip velocity affect both bubble volume and bubble residence time. Consequently, buoyancy flux is a complex function of height. For small bubbles, gas exchange determines plume dynamics to a large extent.

3. Apart from the initial bubble size, the gas flow rate and entrainment coefficient are the parameters to which the model is most sensitive. The sensitivity to diffusor size and initial velocity turned out to be small, provided the initial velocity was chosen below an upper bound. We argue that a reasonable range of the initial velocity is given by the condition $1 < Fr° < 1.7$ for an open source (diffuser situated above the bottom), and $Fr° < 1$ for a closed source (diffusor resting on the bottom).

4. Model calculations clearly define two modes of diffusor operation: oxygenation (or aeration) and artificial mixing. Optimal bubble size depends crucially on the objectives and on the radius-dependent parameters mass transfer and slip velocity. In order to prevent oxygen loss by escaping bubbles and to achieve insertion into the deepest layers for oxygenation, bubbles of radius ≲1 mm are the best choice (here about 0.8 mm). In contrast, artificial mixing is most efficient for an initial bubble radius of about 1 cm.

5. Given the operational goals, the model helps to optimize system design in order to conduct the internal restoration of a lake as economically as possible.

6. The model can be used as a tool to design lake aeration systems and evaluate sensitivity to operation parameters. It can also help in transferring laboratory results to the field. Finally, it serves to define areas where additional research is needed.

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Exhibit C

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HYPOLIMNETIC OXYGENATION: COUPLING BUBBLE-PLUME AND RESERVOIR MODELS

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ABSTRACT

Stratification of reservoirs may result in hypolimnetic oxygen depletion with negative consequences for water quality in hydropower reservoirs, water supply reservoirs, and cold-water fisheries. Although bubble plumes are used to add oxygen to the hypolimnion without significantly disrupting the thermal density structure, they nevertheless introduce energy, which causes mixing. The induced mixing changes the vertical density gradient, and hence the operation of the plume. To account for this effect, a bubble-plume model was coupled in a preliminary fashion with a hydrodynamic reservoir model and then used to predict operational data obtained from Spring Hollow Reservoir in Virginia, USA. The coupled model was able to accurately predict the extent of hypolimnetic warming. Although oxygen consumption was turned off in the reservoir model, the predictions followed the form of the observed oxygen concentration profiles quite closely.

KEYWORDS

Aeration; bubble plume; hypolimnion; mixing, oxygen transfer; reservoir

NOMENCLATURE

C	dissolved concentration, mol m^{-3}.
E	entrainment, $m^2\ s^{-1}$.
F_D	dissolved species flux, mol s^{-1}.
F_G	gaseous species flux, mol s^{-1}.
F_S	salinity flux, g s^{-1}.
F_T	temperature flux, °C $m^3\ s^{-1}$.
g	gravitational acceleration, m s^{-2}.
H	Henry's coefficient, mol m^{-3} bar^{-1}.
K_L	mass transfer coefficient, m s^{-1}.
L	plume length, m.
M	water momentum, $m^4\ s^{-2}$.
N	number flux of bubbles, s^{-1}.
P	pressure, bar.
Q	plume flow rate, $m^3\ s^{-1}$.
r	bubble radius, m.
S	salinity, g kg^{-1}.
T	temperature, °C.

v velocity, m s^{-1}.
W plume width, m.
y gaseous concentration, mol m^3.
z depth, m.

Greek letters

α entrainment coefficient, -.
λ spreading coefficient, -.
ρ density, kg m^{-3}.

Subscripts

a ambient water
b bubble
i gas species, oxygen or nitrogen
p plume water and gas mixture
w plume water

INTRODUCTION

Thermal stratification of lakes and reservoirs can result in substantial hypolimnetic oxygen depletion, which may have a negative impact on cold-water fisheries, the drinking-water treatment process, and water quality downstream of hydropower reservoirs (Little and McGinnis, 2000). One solution to these problems is to install bubble-plume diffusers that replenish hypolimnetic oxygen without destratifying the reservoir (Wüest et al., 1992). While bubble plumes are successful at adding oxygen, the added energy will induce some degree of mixing in the hypolimnion, depending on the design and operational characteristics. The impact of the induced mixing needs to be considered when these systems are designed. For example, partial erosion of the thermocline and warming of the hypolimnion may cause premature destratification of the reservoir. Higher temperatures and plume induced mixing may also be responsible for an increase in hypolimnetic oxygen demand (Little and McGinnis, 2000). Finally, while plume operation changes the thermal structure of the reservoir, the performance of the bubble plume itself depends strongly on the vertical density gradient. This complex interaction between plume and reservoir needs to be taken into account in the design and operation of bubble plumes. In this paper, a preliminary attempt is made to account for this interaction by coupling a model that predicts the performance of a bubble plume with a hydrodynamic reservoir model.

Application of coupled model

The coupled model was tested using data collected from Spring Hollow Reservoir (SHR) located in Roanoke County, Virginia, USA. Spring Hollow is a side-storage reservoir with an existing bubble-plume diffuser that uses air as the source of oxygen (Little and McGinnis, 2000). SHR tends to be mesotrophic and experiences low dissolved oxygen towards the end of the stratified period. Therefore, it is only necessary to operate the diffuser for a period of several weeks in the late summer. Table 1 provides design and operational characteristics. Figures 1 and 2 show temperature and oxygen profiles, beginning on Sep 28 immediately before diffuser start-up. During continuous operation of the diffuser, data were collected on Sep 30, Oct 2, Oct 5, and Oct 9. The diffuser was shut down on Oct 13, but unfortunately no data were collected on that day. Although the diffuser successfully adds oxygen, it is clear that it also causes gentle mixing of the hypolimnion, which in turn causes some warming of the hypolimnetic water. Following shut down, additional data were collected on Oct 21 and Oct 28, showing no further warming of the hypolimnion, but continued depletion of dissolved oxygen. The coupled model should be able to predict

the observed rate of oxygen addition as well as the extent of thermocline erosion and hypolimnetic warming.

Table 1. Operating conditions for bubble-plume diffuser in Spring Hollow Reservoir.

Parameter	Value
Maximum depth [m]	55
Surface area [10^6 m^2]	0.4
Total water volume [10^6 m^3]	7.2
Active diffuser length [m]	360
Average diffuser depth [m]	43
Air flow rate [Nm^3 h^{-1}]*	43

*1 Nm^3 denotes 1 m^3 of gas at 1 bar and 0 °C

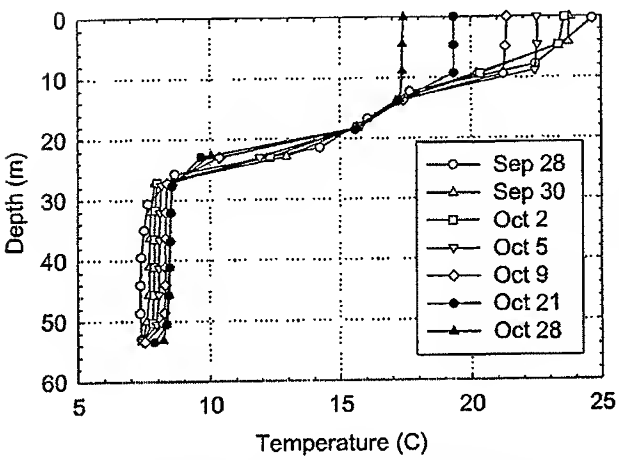

Figure 1. Observed temperature profiles in Spring Hollow Reservoir.

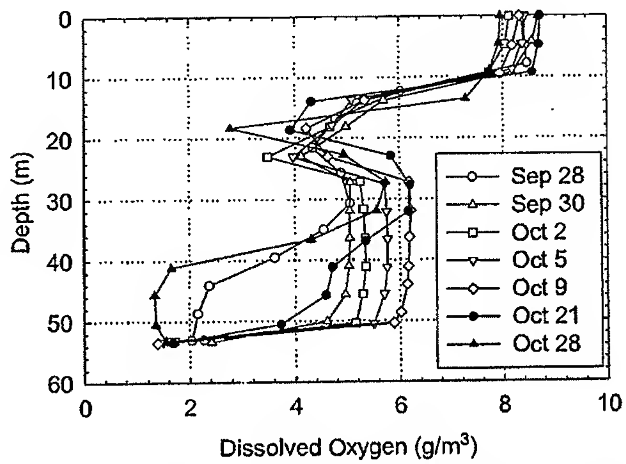

Figure 2. Observed oxygen profiles in Spring Hollow Reservoir.

Plume model

A model for predicting the performance of circular bubble plumes has been developed by Wüest et al. (1992). Based on eight flux equations that are solved simultaneously, the model predicts water flow rate, oxygen transfer and plume rise height, given the diffuser depth, applied gas flow rate, initial bubble size, and diffuser geometry (Wüest et al., 1992). A key contribution of this work was the use of a variable buoyancy flux to account for gas dissolution as well as decompression. This is especially important when pure oxygen is used because the rate of dissolution is very high. The diffuser installed in Spring Hollow Reservoir is linear and the eight model equations (Table 2 and 3) were modified to conform to linear, as opposed to circular, geometry. The entrainment coefficient, α, was set at 0.08 and the spreading coefficient, λ, was 0.85, as reported by Fannelop et al. (1991) for linear plumes. The computational procedure and other details are the same as for the circular plume model (Wüest et al., 1992). Although the linear plume model has not been fully calibrated, the performance was checked by comparing predictions based on a square diffuser with those predicted for a circular diffuser of equal area. Similar results were obtained.